**Final Technical Report**

# *IN SITU* DEVICE FOR REAL-TIME CATALYST DEACTIVATION MEASUREMENTS*

**(DOE Project 422FC2G05NT4229898)**

**Period Performance**
**5/1/05 to 5/31/07**

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# Disclaimer

# Abstract

SCR catalyst management has become an important operations and maintenance activity for coal-fired utility boilers in the United States. To facilitate this activity, a method to determine Catalyst Activity *in situ* is being developed. This report describes the methodology and presents the results of a two ozone season demonstration conducted at Alabama Power Company's Gorgas Unit 10 during the 2005 and 2006 ozone seasons. The results showed that the *in situ* measurements are in good agreement with the laboratory measurements and the technique has some advantages over the traditional laboratory method of determining Catalyst Activity and Reactor Potential. SCR Performance is determined by the overall Reactor Potential (the product of the Catalyst Activity and the available surface area per unit of flue gas). The *in situ* approach provides a direct measurement of Reactor Potential under actual operating conditions, whereas laboratory measurements of Catalyst Activity need to be coupled with estimates of catalyst pluggage and flue gas flowrate in order to assess Reactor Potential. The project also showed that the *in situ* activity results can easily be integrated into catalyst management software to aid in making informed catalyst decisions.

# Acknowledgement

FERCo would like to acknowledge the co-sponsors of this program: US DOE/NETL, EPRI and Southern Company. The input from Charles Miller (NETL), Keith Harrison (Southern Company), and Dave Broske (EPRI) have been key in making this project a success. We also thank Tara Harbin and the operating staff at Plant Gorgas for their efforts and cooperation, without which the work could not have been completed. We also acknowledge the efforts of Joel Brand and Aron Gaus of Brand-Gaus LLC to integrate their gas analysis instrumentation into the *In situ* Testing device.

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# EXECUTIVE SUMMARY

The U.S. utility industry, to date, has installed over 100 GW of selective catalytic $NO_x$ reduction (SCR) systems on coal-fired utility boilers (Cichanowicz, et al., 2006). In the SCR process, ammonia is injected ahead of a catalyst (primarily vanadia-titania based) where it reacts with $NO_x$, forming nitrogen ($N_2$) and water ($H_2O$). In coal-fired SCR systems the Catalyst Activity will gradually decrease over time, primarily due to the constituents in coal flyash. Furthermore, these coal-fired SCR systems contain multiple catalyst layers and each layer can exhibit a different rate of activity degradation. In addition to the decline in activity, with increasing operating hours the catalyst will become plugged with flyash, effectively reducing the active catalyst surface area. As the overall activity of the reactor decreases, a point will be reached where the system will no longer be able to achieve the designed level of $NO_x$ reduction without increasing the ammonia flowrate.

Traditionally, Catalyst Activity is monitored by physically removing catalyst samples from the reactor and testing them in a laboratory. This was easily accomplished while the utilities were operating the SCR reactors on a five-month ozone season basis (May 1 through September 30). However, with the promulgation of the Clean Air Interstate Rule (CAIR) utilities are expected to operate the SCR reactors on a year-round basis, starting in 2009. With year-round operation, opportunities to enter the reactor to obtain samples are reduced. Furthermore, many utilities are extending the interval between major outages to 24 and even 36 months, further reducing the opportunity to obtain catalyst samples for activity testing. Clearly there is a need for the development of new tools and approaches to aid in these catalyst management decisions.

The current project successfully demonstrated a technique to determine Catalyst Activity *in situ*. The project was conducted over two ozone seasons at Alabama Power Company's Gorgas Unit 10.

The *in situ* measurement technique is similar to the traditional laboratory measurement. A small auxiliary ammonia injection grid (AIG) is located above the section of catalyst to be tested. Ammonia is added such that the local $NH_3/NO_x$ ratio exceeds 1.0, and the $NO_x$ reduction across the test section is measured. The measured $NO_x$ reduction for each catalyst layer ($\Delta NO_{xi}$) allows the Reactor Potential to be directly determined for each layer within the reactor ($RP_i$).

$$RP_i = \ln (1 - \Delta NO_{xi})$$

At the beginning of the 2006 ozone season, a new layer of plate catalyst was added to the reactor. This provided a good opportunity to quantitatively compare the *in situ* activity measurements to 1) the activity provided by the catalyst vendor and 2) an activity test by Southern Company's third-party catalyst tester who tested an unused sample of catalyst. The measured *in situ* activity is compared to that reported by the catalyst vendor and third-party catalyst test laboratory in Figure ES-1.

As can be seen in Figure ES-1, the absolute *in situ* activity measurements of the new plate catalyst are in excellent agreement with the vendor's value of activity and the third-party

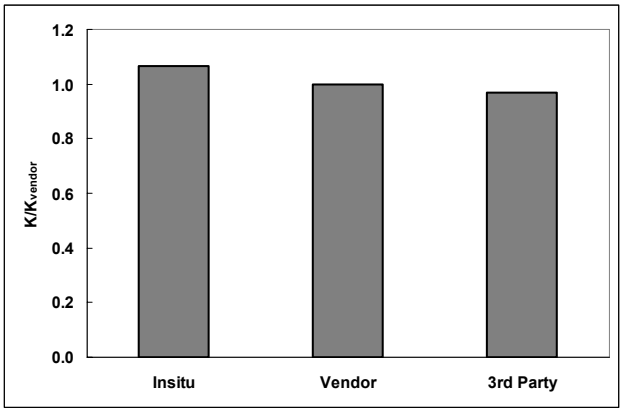
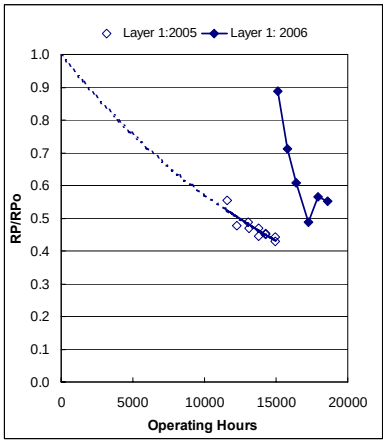



**Figure ES-1. New Plate Catalyst Measured Activity**

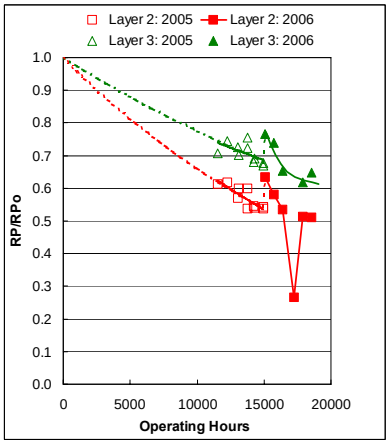
laboratory's measurements. The *in situ* measurements were 6% higher than the value from the vendor while the third-party laboratory's value was 3% lower than the vendor's reported activity.

Figure ES-2 shows the *in situ* results from Layers 1, 2 and 3 over two ozone seasons. The large increase in the Reactor Potential for Layer 1 in 2006 is due to the installation of the new plate catalyst in Layer 1. As can be seen in Figure ES-2, the *in situ* approach provides a comprehensive data set on catalyst deactivation that will improve the ability to make informed catalyst management decisions. With this information utilities should be able to:

- Avoid unscheduled outages to add or replace catalyst. A single unscheduled outage can result in replacement power costs exceeding one million dollars.
- Avoid having to decrease the level of $NO_x$ reduction to maintain required ammonia slip limits. For a 500 MW unit, decreasing $NO_x$ reduction from 90 to 85% could result in $NO_x$ credit purchases of $180,000 to over $400,000 per year, depending on whether the system operates on an ozone season or annual basis.




**(a) Layer 1**




**(b) Layers 2 and 3**

**Figure ES-2. *In situ* Activity Results**

As part of the project the *in situ* activity data was input into EPRI's catalyst management software (CatReact™). A number of case studies were conducted to illustrate the utility of this catalyst management approach.

Commercialization of the *in situ* Catalyst Activity measurement system is in progress.

# 1

# INTRODUCTION

## 1.1 Background

The U.S. utility industry, to date, has installed over 100 GW of selective catalytic $NO_x$ reduction (SCR) systems on coal-fired utility boilers (Cichanowicz, et al., 2006). In the SCR process, ammonia is injected ahead of a catalyst (primarily vanadia-titania based) where it reacts with $NO_x$, forming nitrogen ($N_2$) and water ($H_2O$). In coal-fired SCR systems the Catalyst Activity will gradually decrease over time, primarily due to the constituents in coal flyash. Furthermore, these coal-fired SCR systems contain multiple catalyst layers and each layer can exhibit a different rate of activity degradation. In addition to the decline in activity, with increasing operating hours the catalyst will become plugged with flyash, effectively reducing the active catalyst surface are. As the overall activity of the reactor decreases, a point will be reached where the system will no longer be able to achieve the designed level of $NO_x$ reduction without increasing the ammonia flowrate. This will ultimately result in unreacted ammonia passing through the reactor (i.e., ammonia slip).

Ammonia slip can have detrimental downstream impacts. The ammonia can react with $SO_3$ in the air preheater resulting in ammonium bisulfate formation and air preheater pluggage. The ammonia can also become associated with the flyash to levels such that the flyash can no longer be sold. To avoid these impacts, ammonia slip is typically limited to less than 2 ppm.

As the Catalyst Activity degrades and ammonia slip increases, a point is reached where either additional catalyst must be added to the reactor, or some of the catalyst replaced with new material. To deal with these issues, utilities have undertaken catalyst management programs aimed at monitoring the activity of the catalyst layers within the SCR reactor. This typically involves experimentally monitoring the degradation in activity, as well as utilizing a software component to help plan when catalyst must be added, or replaced.

Traditionally, Catalyst Activity is monitored by physically removing catalyst samples from the reactor and testing them in a laboratory. This was fairly easily accomplished while the utilities were operating the SCR reactors on a five-month ozone season basis (May 1 through September 30). However, with the promulgation of the Clean Air Interstate Rule (CAIR) utilities are expected to operate the SCR reactors on a year-round basis, starting in 2009.

With year-round operation, opportunities to enter the reactor to obtain samples are reduced. Furthermore, many utilities are extending the interval between major outages to 24 and even 36 months, further reducing the opportunity to obtain catalyst samples for activity testing. At the same time, shifting from seasonal to annual operation basically means that in terms of chronological time, the catalyst will be degrading approximately twice as fast. This faster time period coupled with the limited opportunity to obtain samples for testing will exacerbate catalyst management decisions. Clearly, there is a need for the development of new tools and approaches to aid in these catalyst management decisions.

## 1.2 Objectives

The objectives of the present program were two-fold:

- Develop and demonstrate an approach to measure SCR Catalyst Activity *in situ* (within the reactor). This will allow the activity to be determined on a more frequent basis without the need to physically enter the reactor to extract samples.

- Show how the *in situ* Catalyst Activity data can be easily interfaced with catalyst management software (in this case, EPRI's CatReact™ software) to aid in making catalyst management decisions.

## 1.3 Approach

The program objectives were successfully achieved through a two ozone season (2005 and 2006) development and demonstration at Alabama Power's Gorgas Unit 10. During the first ozone season, the approach to measuring the catalyst *in situ* was demonstrated on a proof of concept basis. This was accomplished using primarily portable test instrumentation. For the second ozone season, the *in situ* measurements were continued but with more sophisticated hardware that is expected to be incorporated into a commercial system.

The *in situ* activity data were then compared to the results of the laboratory analysis of catalyst samples removed from the reactor. The laboratory analysis was provided by a third-party catalyst test laboratory contracted by the host utility.

Finally, the *in situ* activity data was incorporated into EPRI's CatReact™ software. This is a spreadsheet-based program designed to facilitate catalyst management decisions. Two case studies are presented in Section 6 of this report to demonstrate the utility of this approach.

# 2

# METHODOLOGY AND APPROACH

## 2.1 Catalyst Activity and SCR Reactor Potential

Before discussing the approach for the *in situ* activity measurement, it is important to understand the parameters that dictate SCR performance. This subsection will discuss the various parameters that are important in determining the overall performance of an SCR system. In particular, the parameters that are of most importance are 1) Catalyst Activity, 2) Reactor Potential, and 3) area velocity.

To understand the importance of these parameters, consider a mathematical analysis of the processes that occur as the $NH_3$-$NO_x$ mixture flows through a catalyst passage. The following processes take place as the gas enters a catalyst channel:

1. The flue gas enters the catalyst channel with a concentration $NO_{x_{in}}$

2. Before the $NO_x$ can react with $NH_3$ on one of the "active" sites on the catalyst surface, it needs to migrate from the bulk gas to the surface of the catalyst. This is a mass transfer process that is described by equation 2-1 below. This mass transfer process occurs continuously along the length of the channel.

$$\begin{bmatrix}\text{Rate of } NO_x \\ \text{mass transfer} \\ \text{to the catalyst} \\ \text{surface}\end{bmatrix} = h_m A_{surface} \left( C_{NO_{x_{gas}}} - C_{NO_{x_{surface}}} \right) \qquad (2\text{-}1)$$

$h_m$ = mass transfer coefficient (depends on gas velocity and catalyst geometry)
$A_{surface}$ = surface area of the catalyst channel
$C_{NO_{x_{gas}}}$ = $NO_x$ concentration in the gas phase
$C_{NO_{x_{surface}}}$ = $NO_x$ concentration on the surface

3. Once the $NO_x$ reaches the surface of the catalyst, it will diffuse through the porous structure of the catalyst, and attach to an active site where it will react with $NH_3$. The $NH_3$ will have gone through the same steps as the $NO_x$ in terms of diffusing from the bulk gas to the catalyst surface. The rate of reaction of the $NO_x$ on the surface is described by equation 2-2 below.

$$\begin{bmatrix}\text{Reaction Rate} \\ \text{of } NO_x \text{ on the} \\ \text{surface}\end{bmatrix} = - K_{chem} \; A_{surface} \; C_{NO_{x\,surface}} \qquad (2\text{-}2)$$

$K_{chem}$ = chemical reaction rate constant that also accounts for pore diffusion

To solve these equations, it is assumed that the system is at steady state (i.e., at any place on the catalyst, conditions do not change with time). For this to be true, the rate of mass transfer to the surface must be equal to the rate of reaction; otherwise, the surface concentration would change with time. If equation 2-1 is set equal to equation 2-2, the surface concentration of $NO_x$ may be calculated from:

$$C_{NO_x surface} = \frac{1}{1 + \frac{K_{chem}}{h_m}} \quad C_{NO_x gas} \tag{2-3}$$

When these two relations (i.e., equations 2-1 and 2-2) are integrated along the entire length of the channel, the $NO_x$ concentration exiting the channel can be calculated and thus the $NO_x$ reduction determined. This results in the following relation for $NO_x$ reduction

$$\Delta NO_x = 1 - e^{-\frac{1}{A_V}\left[\frac{1}{\frac{1}{K_{chem}} + \frac{1}{h_m}}\right]} \tag{2-4}$$

$\Delta NO_x$= $NO_x$ reduction expressed as a fraction
(or multiplied by 100 to be expressed as percent)

$A_v$= Area velocity, or flowrate through the channel divided by surface the area of the channel

The term in brackets with $K_{chem}$ and $h_m$ is defined as the Catalyst Activity (K). Note $K_{chem}$ in Equation 2-5 includes mass transfer through the catalyst pores as well as the reaction on the active surface.

$$K = \frac{1}{\frac{1}{K_{chem}} + \frac{1}{h_m}}$$

$$\Delta NO_x = 1\text{-}e^{-K/Av} \tag{2-5}$$

The area velocity essentially defines the flue gas flowrate per unit catalyst surface area in the reactor:

$$A_v = \frac{Q}{A_{cat}} \tag{2-6}$$

$$= \frac{Q}{V_{cat} A_{sp}} \tag{2-7}$$

$A_v$ = area velocity, m/hr

Q = flue gas flowrate, $m^3$/hr at standard conditions

$A_{cat}$ = catalyst surface area, $m^2$
$V_{cat}$ = catalyst volume, $m^3$
$A_{sp}$ = catalyst specific surface area $m^2/m^3$

The specific surface area, $A_{sp}$, is the superficial area of the catalyst channel and does not include the catalyst pore area. As noted above, the catalyst pore mass transfer is included in

the $K_{chem}$ term. Note that the activity K, involves both the chemical activity on the surface of the catalyst and the mass transfer processes in the channel. Thus, the Catalyst Activity is not a fundamental property of the catalyst material, since geometry and velocity can influence the mass transfer coefficient ($h_m$). In particular,

- The same material fabricated with different channel openings will exhibit different activities.
- The same material and geometry with different flowrates (i.e., velocity) in the channel will exhibit different activities.

The overall reactivity of an SCR system is determined by a term referred to as the Reactor Potential (RP). The Reactor Potential is the Catalyst Activity multiplied by the total surface area of catalyst per unit of flue gas.

$$RP = \frac{K A_{sp} V_{cat}}{Q} = \frac{K}{A_v} \tag{2-8}$$

The Reactor Potential is a measure of the overall ability of the reactor to reduce $NO_x$. A certain level of Reactor Potential is needed to achieve a set $NO_x$ reduction while limiting $NH_3$ slip to a specified level.

For an SCR reactor with multiple layers, the overall Reactor Potential is the sum of the Reactor Potential of each layer.

$$RP = \sum_{\text{i layers}} RP_i = \sum_{\text{i layers}} \frac{K_i}{A_{vi}} \tag{2-9}$$

Additionally, since some of the catalyst surface area for each layer will be lost due to plugging by flyash, equation 2-9 needs to be modified to account for this blockage.

$$RP = \sum_{\text{i layers}} \frac{K_i \, A_{cat_i}^{clean} \left(1 - B_i\right)}{Q} = \sum_{\text{i layers}} \frac{K_i \left(1 - B_i\right)}{A_{vi}^{clean}} \tag{2-10}$$

where, $A_{cat_i}^{clean}$ = Total surface area of the $i^{th}$ layer without blockage

$B_i$ = Fraction of the catalyst channels on the $i^{th}$ layer that are blocked

$A_{vi}^{clean}$ = Area velocity of the $i^{th}$ layer without blockage

Equation 2-10 provides a means to characterize the overall potential of an SCR reactor to remove $NO_x$. The Reactor Potential inherently accounts for both catalyst deactivation ($K/K_o$), as well as catalyst layer blockage, thereby providing a true assessment of the operating condition of the SCR reactor.

## 2.2 Laboratory Determination of Catalyst Activity and Reactor Potential

Traditionally, in order to determine the Reactor Potential, a utility will remove a sample of catalyst from each layer of the reactor. The samples are then sent out to a laboratory for an activity analysis. This is accomplished by placing the sample in a device that allows a flue gas stream (real or simulated) to be passed through the sample at temperature, $NO_x$, and flow conditions representative of those for the full-scale SCR reactor. Ammonia is injected ahead of the sample at a $NH_3/NO_x$ ratio of 1.0 or 1.2, and the $NO_x$ reduction across the sample is measured. The activity for the sample is then calculated by rearranging equation 2-5:

$$K = -A_v \ln (1 - \Delta NO_x) \qquad (2\text{-}11)$$

Where $A_v$ = the area velocity at which the laboratory test was conducted (generally corresponding to the design area velocity)

$\Delta NO_x$ = the $NO_x$ reduction measured in the laboratory apparatus

Once the activity of each individual layer ($K_i$) is calculated using equation 2-11 above, all that is needed to determine the overall Reactor Potential from Equation 2-10 is an estimate of the blockage for each of the catalyst layers ($B_i$). Generally, this is accomplished by conducting a visual inspection of the reactor, and this procedure will be discussed in more detail in Section 5. One important thing to note at this point in time however, is that when utilizing equation 2-10, the precision of the Reactor Potential calculation depends as much on the accuracy of the blockage estimate as it does on the determination of K.

## 2.3 *In situ* Determination of Reactor Potential and Catalyst Activity

Currently, most utilities operate their SCR systems only during the five-month ozone season. In most cases, the seven-month non-operating season generally provides ample time to remove catalyst samples from the reactor, send them out for testing, receive the activity results, and if necessary, take corrective action by adding or replacing catalyst material prior to the next ozone season. However, this best-case scenario still only allows one data point per layer, per year. Most utilities will be required to move to year-round operation of their SCR systems by 2009. This, combined with the trend of stretching the scheduling of major outages out to as far as 24 to 36 months, will result in far fewer opportunities to go inside the reactor to remove catalyst samples for activity analysis, as well as to assess the blockage of the layers.

Fossil Energy Research Corp. (FERCo) has developed a new device (U.S. patent pending, patent application 20050255605) that allows the Reactor Potential and Catalyst Activity to be determined *in situ*. With this new approach to catalyst testing, the Reactor Potential and activity can be measured at any time, independent of unit outages. With multiple devices, each layer can be measured independently and a number of individual measurements can be made across a given catalyst layer.

Unlike the laboratory approach that measures the activity (K), and then uses the design area velocity ($A_v$) with an estimate of the blockage to calculate the Reactor Potential, this new device provides a direct measurement of Reactor Potential. The *in situ* measurement technique is similar to the laboratory measurement. A small auxiliary ammonia injection grid (AIG) is located above the section of catalyst to be tested. To make the measurement, ammonia is added such

that the local $NH_3/NO_x$ ratio exceeds 1.0, and the $NO_x$ reduction across the test section is measured. This is illustrated in Figure 2-1 where these individual test modules are incorporated on each catalyst layer. Incorporating the expressions for Reactor Potential and Catalyst Activity in equations 2-9 and 2-11 above yields the following expression, which indicates that Reactor Potential can be directly determined by measuring the $NO_x$ removal across the *in situ* test module.

$$RP_i = \ln (1 - \Delta NO_{xi}) \tag{2-12}$$

It is important to note that this calculation results in the true Reactor Potential value accounting for the actual flue gas flow rate and blockage values, not a calculated quantity based on the design area velocity and an estimate of the blockage.

## 2.4 Laboratory Versus *In situ* Determination of Reactor Potential and Catalyst Activity

The prior two subsections described the current practice of determining Catalyst Activity and Reactor Potential, as well as the new *in situ* approach. While superficially the measurements appear similar (except for the fact that the *in situ* measurement is performed in the full-scale reactor), there are some fundamental differences that warrant further discussion.

The differences in these two approaches are illustrated in Figure 2-2. For catalyst management one needs to know the overall Reactor Potential. In the traditional approach (Figure 2-2a), a laboratory measurement is made of the Catalyst Activity K. The Reactor Potential is then calculated using an estimate of the blockage of each layer along with the design area velocity. If the estimate of blockage is inaccurate, or if the actual flue gas flowrate differs from the design value, the calculated Reactor Potential will be in error.

On the other hand, the *in situ* approach provides a direct measurement of the actual Reactor Potential (Figure 2-2b). This measurement inherently accounts for the actual flue gas flowrate, and the actual blockage of the catalyst layer.

If one wanted to determine the Catalyst Activity from the *in situ* measurement then an estimate of the blockage and the design area velocity would be used to calculate $K_i$ (Figure 2-3) utilizing the following relationship.

$$K_i = \frac{RP_i \; A_{vi}}{(1 - B_i)} \tag{2-13}$$

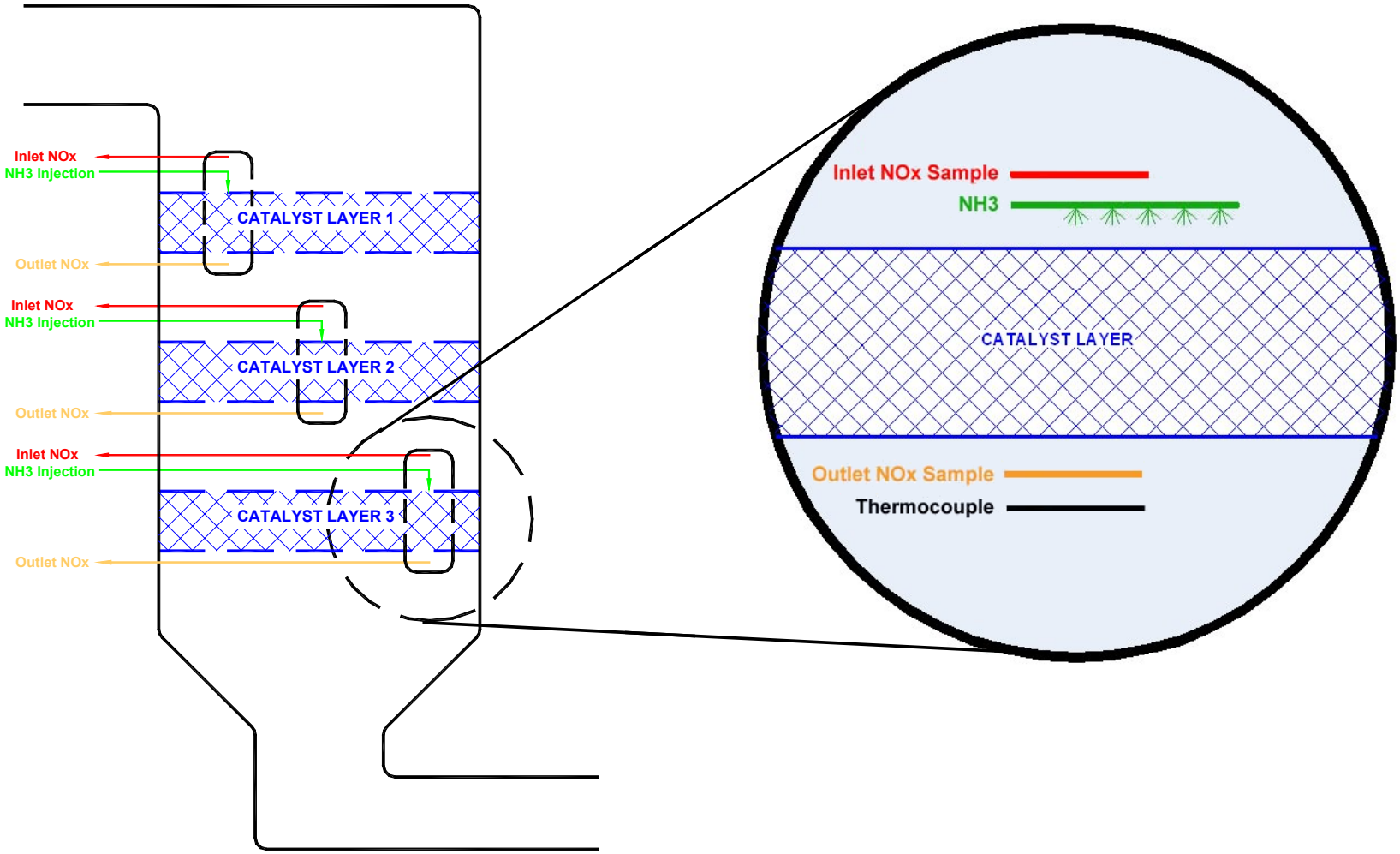
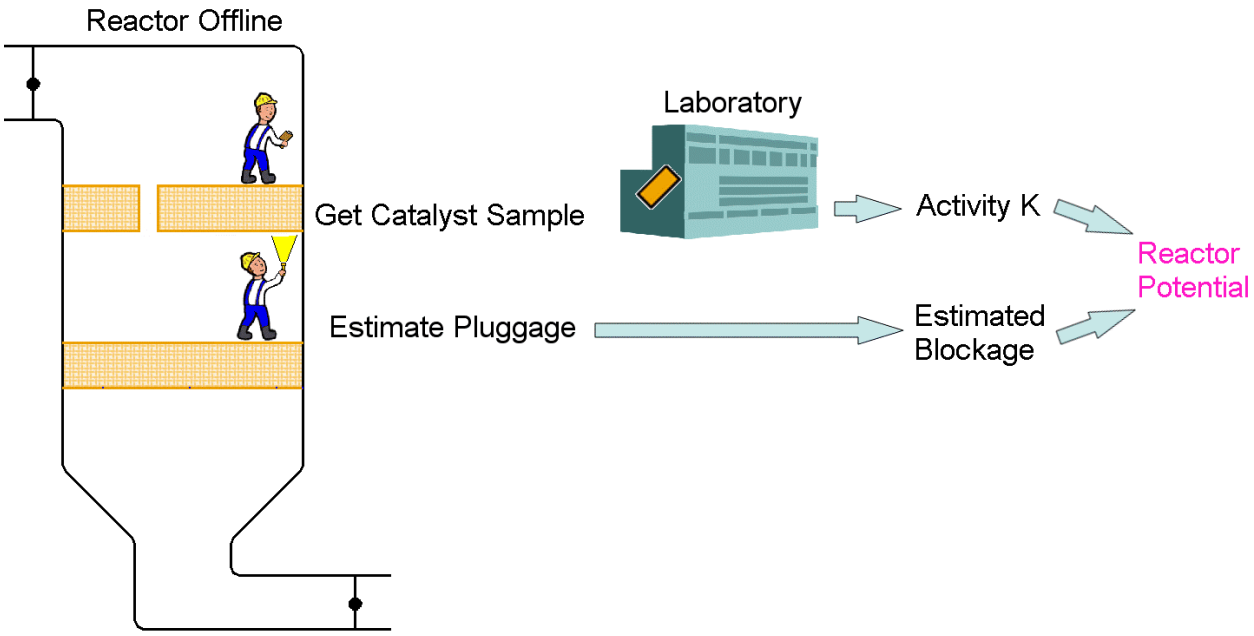
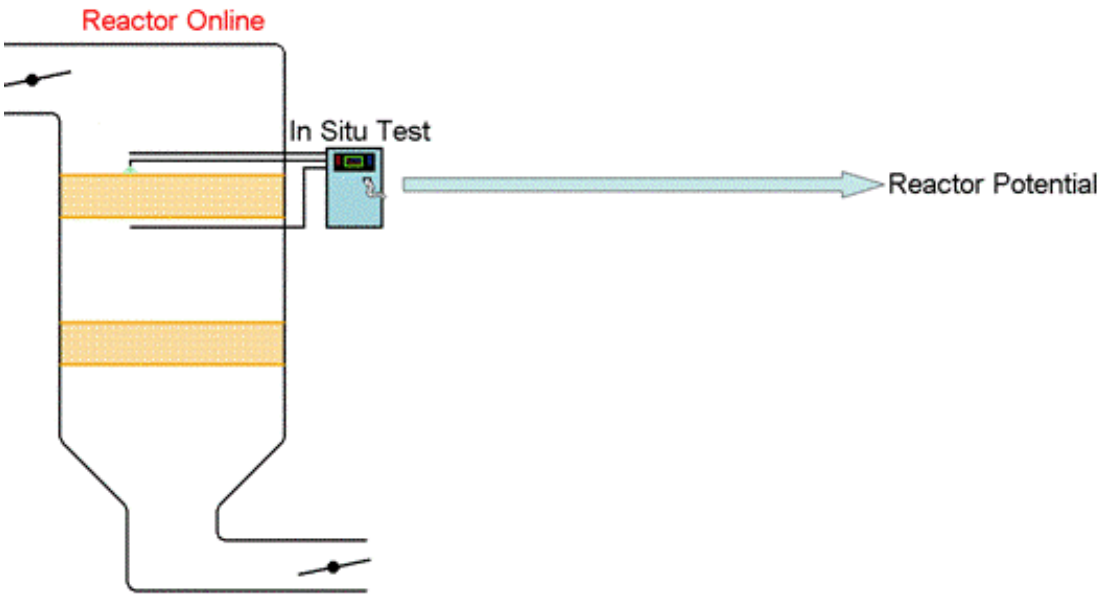



**Figure 2-1. *In situ* Determination of SCR Reactor Potential**




**(a) Traditional Laboratory Determination of Reactor Potential**




**(b) *In situ* Determination of Reactor Potential**

**Figure 2-2. Laboratory and *In situ* Determination of Reactor Potential**

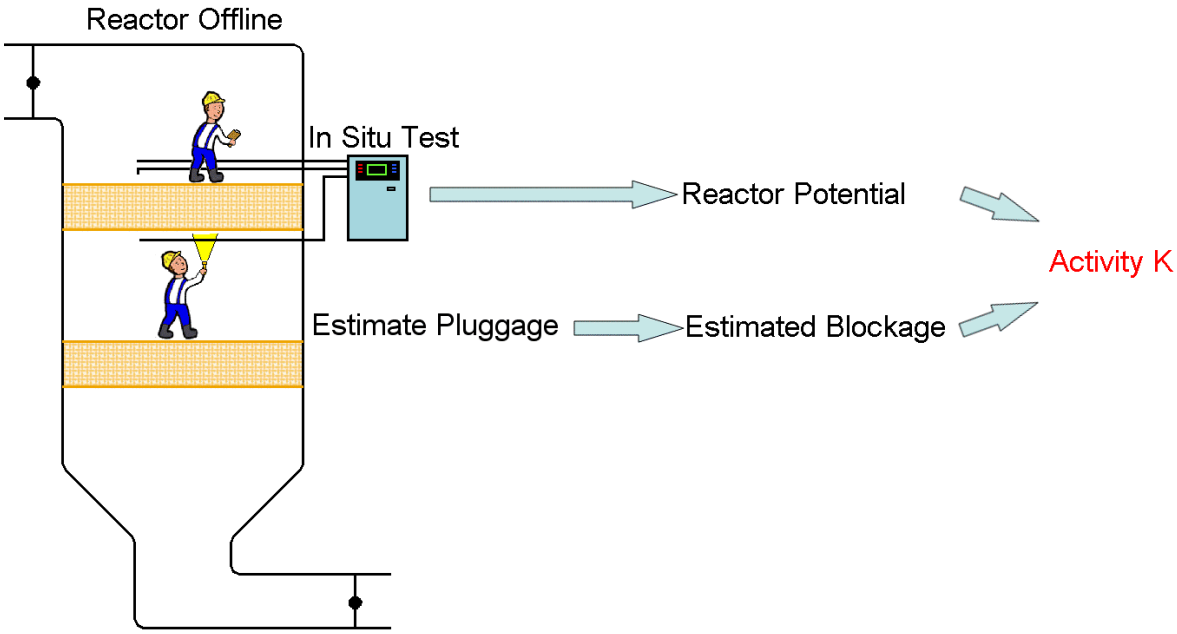



**Figure 2-3. Determining Catalyst Activity from the *In situ* Reactor Potential Measurement**

# 3

# FIELD DEMONSTRATION

## 3.1 Overall Structure of the Field Demonstration

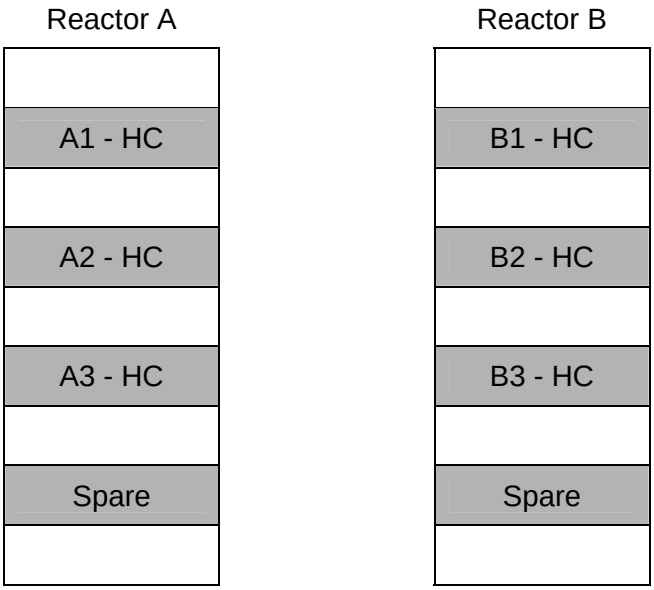
The field demonstration of the *in situ* Catalyst Activity measurement methodology was conducted over the 2005 and 2006 ozone seasons at Alabama Power Company's Gorgas Unit 10.

Gorgas Unit 10 is a 700 MW tangentially-fired boiler that started operation in 1972 and burns an Alabama bituminous coal. The unit was retrofit with an SCR system that began ozone season operation in May 2002. The Gorgas Unit 10 system is a 3 + 1 design with two separate reactors (A and B). Three layers of extruded honeycomb catalyst were initially installed with room for a spare layer. Prior to the start of the 2006 ozone season, a new layer of plate catalyst was added to the top layer, and the "used" top layer was moved down to the fourth (spare layer) location in the other reactor. In this move, the top layer in the A reactor was moved to the bottom layer in the B reactor, and vice versa. This is illustrated in Figure 3-1.

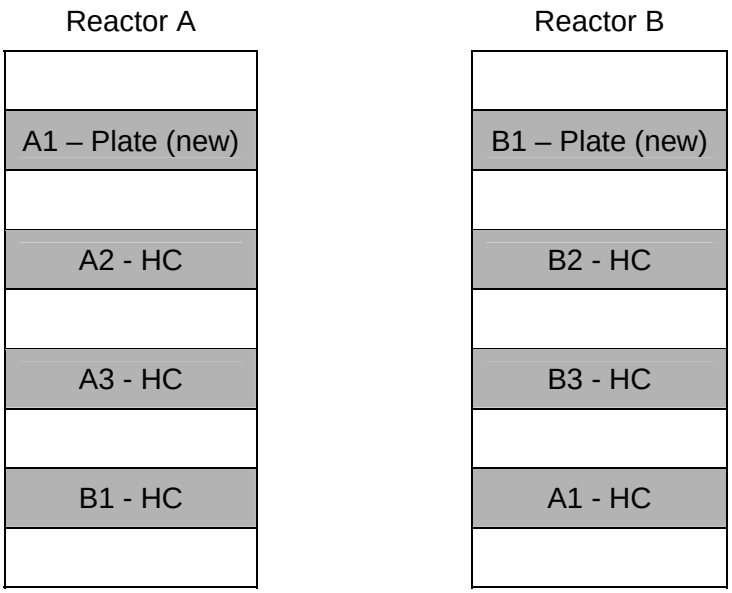
The *in situ* measurements began at the start of the 2005 ozone season. At this time the original three layers of honeycomb catalyst in each reactor had accumulated nominally 11,500 hours of operating time. The *in situ* measurements continued through the 2006 ozone season which corresponds to an accumulated operating time of nominally 18,600 hours.

The *in situ* measurement program was performed in two phases, each comprising a full ozone season. The first phase during the 2005 ozone season was a proof-of-concept phase. Three *in situ* activity modules were installed in the B reactor, one on each of the three original catalyst layers. A portable, electrochemical-based NO and $O_2$ emissions analysis system was used to measure the Catalyst Activity on a monthly basis throughout the 2005 ozone season. The primary objective of this proof-of-concept phase was to determine the overall viability of the *in situ* measurement approach.

Following the 2005 proof-of-concept tests, the second phase of the testing took place during the 2006 ozone season. This test phase involved adding additional test modules to the B reactor such that there were two modules on each of the four catalyst layers (3 honeycomb and 1 plate), for a total of eight test modules. In addition, a more commercial version of the measurement and control system was designed and fabricated. This latter system included an integrated system with data acquisition and control equipment with the potential to allow the activity testing to be performed remotely, via the internet.




(a) Initial Catalyst Loading (HC = honeycomb)




(b) Catalyst Addition Prior to 2006 Ozone Season

**Figure 3-1. Gorgas Unit 10 Catalyst Arrangement**

## 3.2 Measurement Hardware

A. Proof of Concept Hardware

During the 2005 ozone season proof-of-concept tests, a portable electrochemical system was used to measure NO and $O_2$ at the inlet and outlet of the modules. A photograph of this equipment is shown in Figure 3-2. As can be seen in the photograph, the inlet and outlet of each module was sampled simultaneously (as represented by the two rotameters seen in Figure 3-2), and analyzed for NO and $O_2$ with electrochemical cells. The output from the cells was recorded on a data logger. This measurement hardware was intended for proof-of-concept testing, and not indicative of anticipated commercial hardware.

B. 2006 Ozone Season Hardware

Following the 2005 ozone season proof-of-concept tests, a measurement system was designed and fabricated that more closely modeled what was anticipated for a commercial system. Figure 3-3 shows a photograph of the hardware used for the 2006 ozone season tests.

The hardware designed for this program consists of two modules, as shown in Figure 3-3. The module on the right side of the photograph, with the external air conditioner, accepts all of the sample lines from the test modules, and provides the ammonia supply lines to the small supplemental AIGS. This module also contains the computer controlled switching valves to switch from one test module to the other along with the back-purge valves.

The smaller module on the left contains a dual channel NO/$O_2$ measuring system with sample conditioning, an ammonia mass flow controller, and the data acquisition and control systems.

This dual module arrangement, shown in Figure 3-3, is commercially intended for a site with multiple SCR units. In this case, a valve module (right side of Figure 3-3) would be permanently located at each SCR. The module on the left (NO/$O_2$ analyzers, etc.) would then be moved from unit to unit. This should reduce overall costs for a site with multiple units as only one set of analyzers would have to be purchased. For a site containing a single SCR, both modules shown in Figure 3-3 would be incorporated into a single enclosure. In terms of the number of test modules, it is anticipated that a utility will choose to have one to two test modules per catalyst layer.

Features of the 2006 test hardware include:

- Dual-channel chemiluminescent NO and zirconia oxide $O_2$ analyzers manufactured by Brand Gaus LLC.
- Thermoelectric sample conditioner.
- PLC/data acquisition system with Ethernet communications capabilities.
- Computer controlled valves for sample acquisition and ammonia feed.
- Differential pressure transducer to measure layer to layer pressure drop.
- System controlled via a notebook computer.

**Figure 3-2. Proof-of-Concept Hardware, 2005 Ozone Season**

**Figure 3-3. 2006 *In situ* Activity Hardware**

With minor modification, it is anticipated that the hardware used for the 2006 ozone season tests to be similar to a commercial offering. Figure 3-4 shows a screen shot from the data acquisition software that was developed for this system.

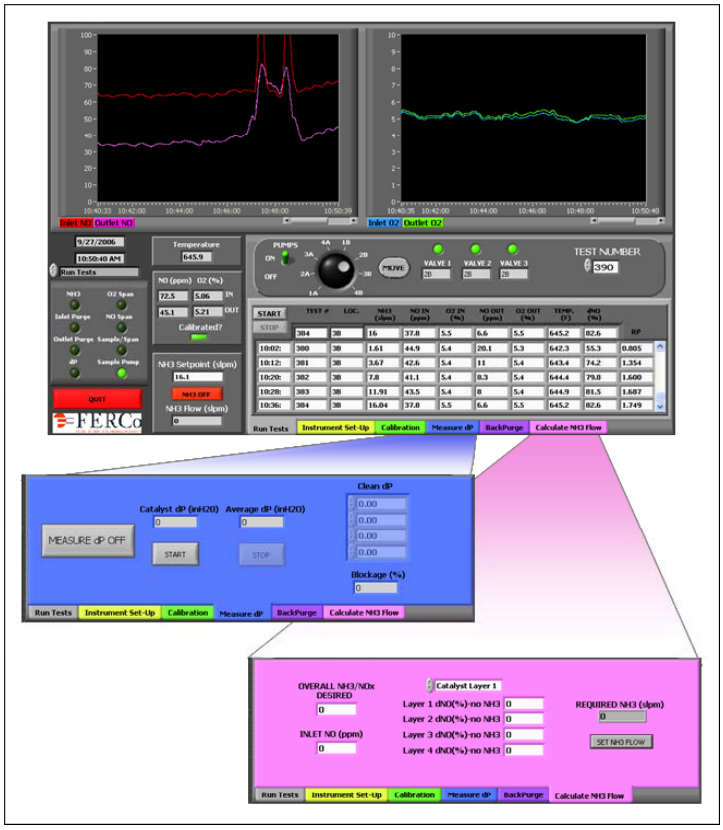



**Figure 3-4. Date Acquisition and Control Screen, 2006 Ozone Season**

# 4

# *IN SITU* RESULTS

The goal of the *in situ* test methodology is to measure the Reactor Potential of each layer under the operating conditions of the full-scale SCR reactor. This is accomplished by creating a small region on each layer where the $NH_3/NO_x$ ratio is greater than 1, thereby allowing the measurement of the maximum $NO_x$ removal across the catalyst, and thus the direct determination of the Reactor Potential for that particular layer. While the host-unit boiler is not in any way controlled during these tests (i.e. load blocked), the tests are run during full-load operation in order to best emulate the SCR design conditions (i.e. the design $A_v$).

As indicated previously in Section 2, since the *in situ* Reactor Potential measurements are performed on the full-scale SCR, the results reflect the true operating conditions and $NO_x$ removal performance of the SCR reactor accounting for the effects of catalyst deactivation, blockage of the individual layers, and the actual flue gas flowrate through the catalyst.

One significant difference between the *in situ* and laboratory methods is that the *in situ* technique is not as controlled or spatially well-defined. In the laboratory, it is relatively easy to set an $NH_3/NO_x$ ratio of 1.0 or 1.2 since the gas flowrates are all well controlled and catalyst test sample is completely enclosed in a housing. With the *in situ* test module, there are no walls to prevent the additional $NH_3$ injected via the test module AIG from diffusing out from the test area. Thus, simply setting the test $NH_3/NO_x$ ratio to 1.0 based upon the bulk flue gas flowrate and the $NO_x$ concentration at the inlet of the test section, does not guarantee the point of maximum $NO_x$ removal will be achieved. Furthermore, there may be excess, unreacted $NH_3$ from the host unit's AIG that has passed through the catalyst layer above, and is now entering the test region on the layer below. For these reasons, the $NH_3$ flowrate required to achieve the maximum $NO_x$ removal point cannot be calculated, but rather must be determined experimentally for each individual *in situ* test location.

As described previously, $NO_x$ removals were measured using either electrochemical-based sensors or chemilumenescent and zirconia oxide analyzers for NO and $O_2$ only. Ammonia and $NO_2$ were not measured during either phase of the test program. Gas sampling was conducted at the inlet and outlet of each test module as indicated in Figure 2-1. The gas sampling and analysis package for both phases of the test program housed two separate NO and $O_2$ analysis systems, allowing the simultaneous measurement of inlet and outlet conditions.

## 4.1 Initial *In situ* Test Protocol

A. Initial Test Protocol

To best characterize the $NO_x$ removal response as a function of $NH_3$ injection rate, a specific testing protocol was followed for each *in situ* test location during the initial phase of tests run during the 2005 ozone season. First, the $NO_x$ removal across the test module was measured without any additional $NH_3$ injection through the module AIG. Once this baseline $NO_x$ removal

was characterized, $NH_3$ was added incrementally via the test module AIG and the $NO_x$ removal monitored until the point of maximum $NO_x$ removal was achieved. Once the maximum $NO_x$ removal was determined, the Reactor Potential for the catalyst layer was calculated via:

$RP_i = -\ln(1-\Delta NO_{xi})$.

Figure 4-1 shows the results of a typical set of $NO_x$ removal measurements utilizing the test protocol outlined above. For each of the three test locations, the $NO_x$ removal is presented as a function of the test module $NH_3/NO_x$ ratio, which is calculated based upon the $NH_3$ injected through the test module AIG only (i.e. does not include the $NH_3$ already in the flue gas from the SCR reactor's full-scale AIG). The Gorgas Unit 10 SCR system is typically operated at 85% $NO_x$ removal overall. Figure 4-1 shows that under this condition, the baseline $NO_x$ removal levels across layers 1, 2, and 3 are nominally 68%, 42%, and 8%, respectively. These variations in removal through the reactor are expected as the full-scale AIG is located ahead of the first layer, and while the $NO_x$ levels decrease as the flue gas moves through the reactor, the amount of unreacted $NH_3$ decreases at a faster rate. Thus, the overall $NH_3/NO_x$ ratio decreases as the flue gas passes through the reactor. Note the baseline $NO_x$ reduction measurements of 68%, 42%, and 8% across layers 1, 2, and 3 corresponds to an overall $NO_x$ removal of 83%.

As the $NH_3/NO_x$ ratio is increased at each test location by injecting additional $NH_3$ via the test module AIG, the $NO_x$ removal for that test location is seen to increase and eventually level out at a maximum value. For the particular set of tests shown in Figure 4-1, the maximum $NO_x$ removal rates are nominally 77%, 87% and 91% for layers 1, 2 and 3, respectively. In multiple-layer, full-scale SCR systems, it is expected that the catalyst deactivation rates will be higher for the "upstream" layers in the reactor, and the maximum $NO_x$ removals shown in Figure 4-1 confirm this expectation. Recall that both K and RP are a function of the relationship: $-\ln(1-\Delta NO_x)$. Thus, as the maximum $NO_x$ removal increases, both the Catalyst Activity and Reactor Potential for that layer increase.

B. Final *In situ* Test Protocol

Running the $NO_x$ removal versus $NH_3/NO_x$ ratio curve is a time consuming process, and an entire day is required to run a complete set of tests for all three catalyst layers as shown in Figure 4-1. The monthly $NO_x$ removal testing at Gorgas Unit 10 was conducted over a period of two days, with each day resulting in a $NO_x$ removal curve for each of the three test modules. A review of the first four sets of test results indicated that while the basic shape of the curve was consistent with time for each catalyst layer, the maximum $NO_x$ removals varied slightly. In order to better understand these variations, the daily test protocol for each layer was modified. After the initial baseline $NO_x$ removal measurement, rather than incrementally increasing the $NH_3$ injection rate, the injection rate was set at a value high enough to assure reaching the maximum $NO_x$ removal point, and then four to five repeat tests were run at this condition. The "high" $NH_3$ injection rate for these tests was determined by reviewing the multiple $NO_x$ removal curves previously developed for the individual catalyst layers.

Figure 4-2 presents the results of a typical set of $NO_x$ removal measurements utilizing the modified test protocol outlined above. The tests for each catalyst layer were conducted over a time span of one to two hours, and results indicate very little variation in the $NO_x$ removals measured over that period of time. The average $NO_x$ removals measured for catalyst layers 1, 2, and 3 were nominally 73%, 80% and 86%, respectively. The specific set of data shown in Figure 4-2 was collected at the end of the 2005 ozone season, and it can clearly be seen that

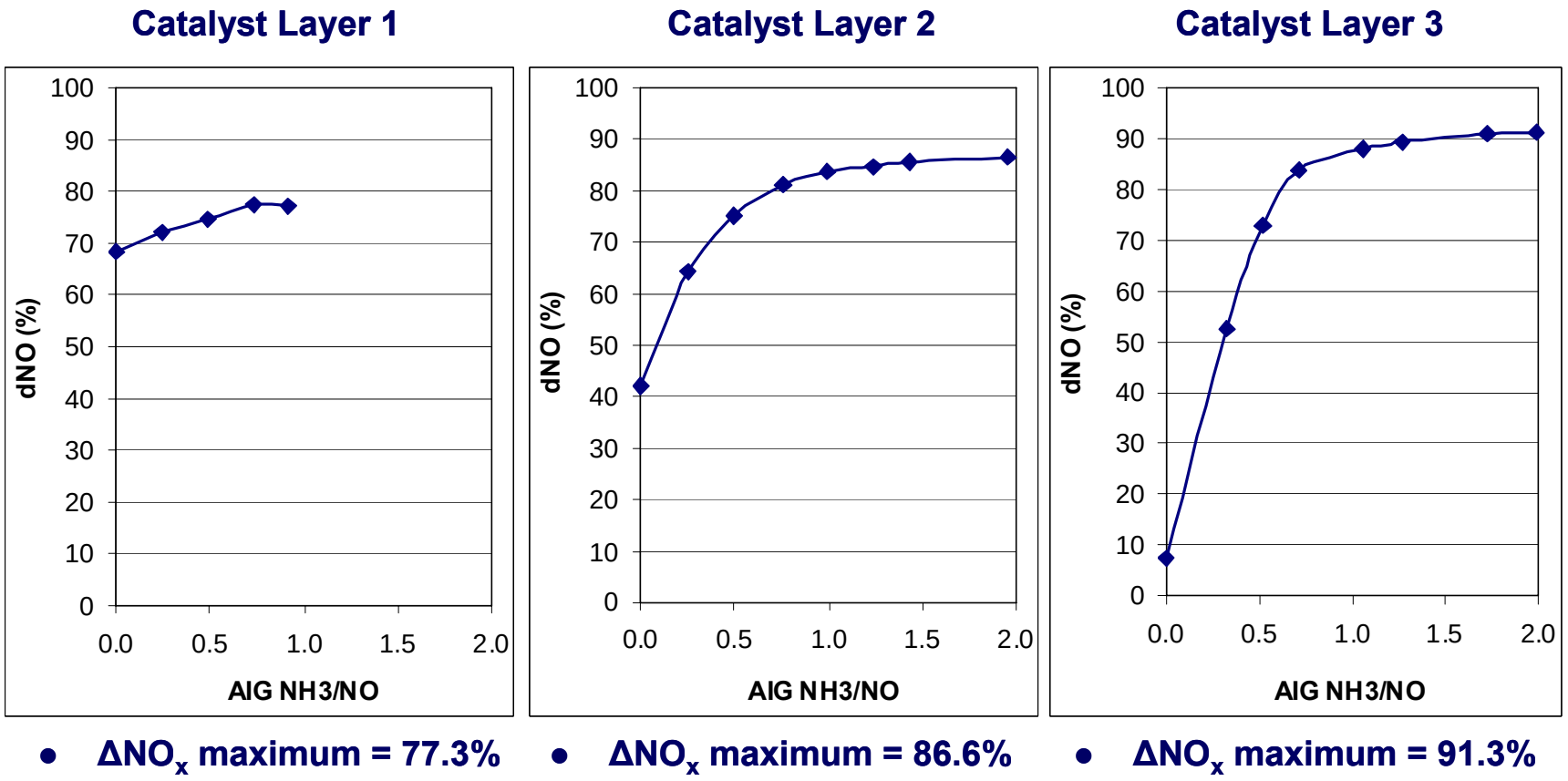



**Figure 4-1. *In situ* $NO_x$ Removal as a Function of $NH_3$ Injection Rate**

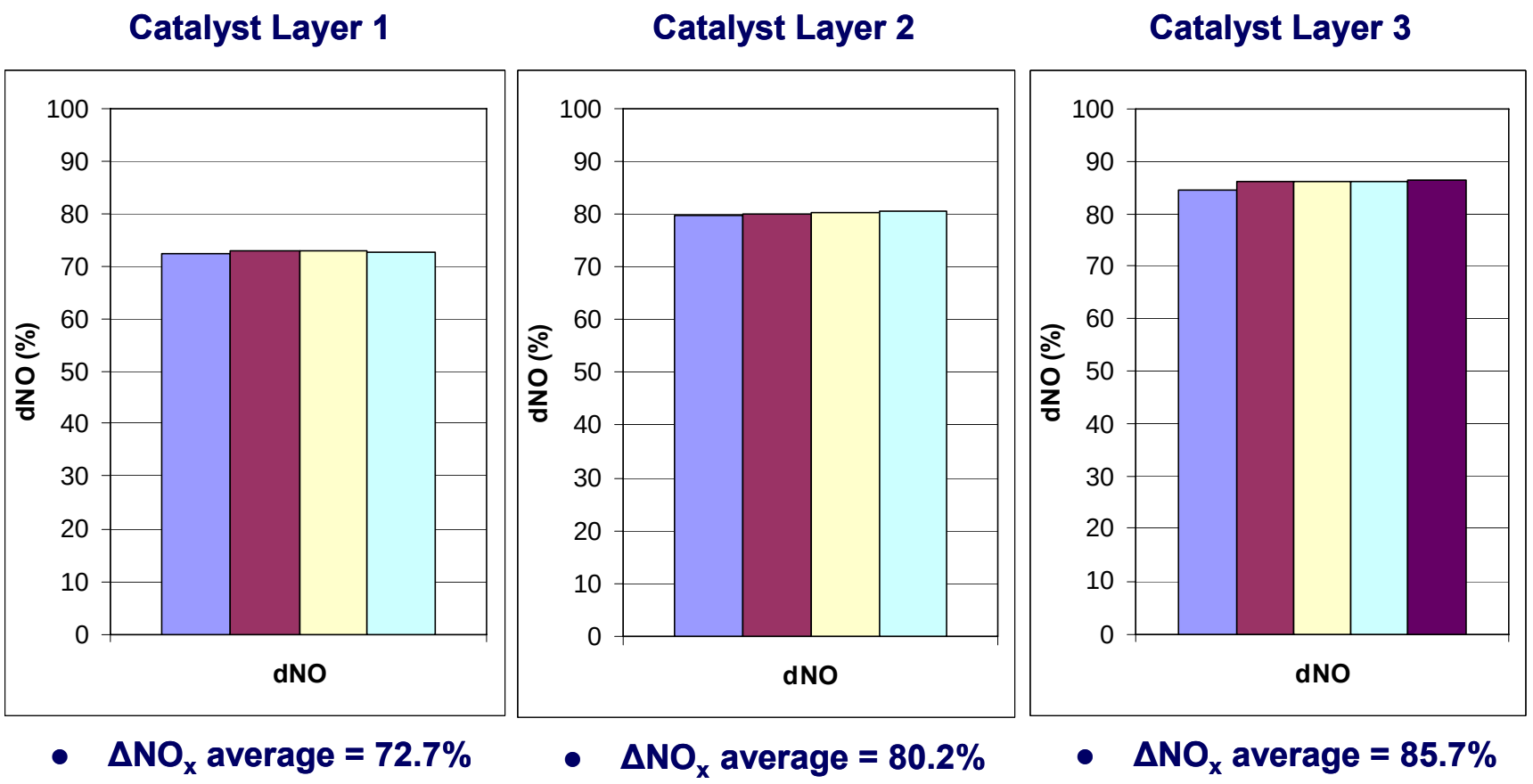



**Figure 4-2. Typical Repeatability of *In situ* $NO_x$ Removal Test Results**

the average maximum $NO_x$ removals for each layer have decreased from the levels measured early in the 2005 ozone season (i.e. Figure 4-1), indicating that both the Catalyst Activity and Reactor Potential for each layer have decreased.

## 4.2 2005 Ozone Season *In situ* Test Results

Site visits were conducted on a monthly basis throughout the 2005 ozone season in order to monitor the Reactor Potential of each the three catalyst layers. The outcome of this set of tests is shown in Table 4-1 and Figure 4-3, where the results are presented on the basis of relative Reactor Potential ($RP/RP_0$) versus operating hours. $RP_0$ is defined as the Reactor Potential corresponding to when the catalyst was new and freshly installed in the reactor. Recall the Gorgas Unit 10 SCR reactor began operation in May of 2002 for that year's ozone season. Thus, all three catalyst layers had accumulated nominally 11,500 hours of exposure prior to the start of the *in situ* test program beginning in May of 2005. For the purposes of this test program, $RP_0$ is calculated based upon the new Catalyst Activity ($K_0$) measured by Southern Company's third-party catalyst testing organization, and a full-scale area velocity value calculated for Gorgas Unit 10 based upon the coal analysis and full-load fuel feedrate data provided by plant personnel for May of 2005. The results are presented on the basis of $RP/RP_0$ in order to avoid revealing the actual RP data, which Southern Company considers proprietary.

**Table 4-1. *In situ* Results: 2005 Ozone Season**

| 2005 Ozone Season Insitu Data | | | | | |
|---|---|---|---|---|---|
| Test Date | Operating Hours | Honeycomb Layer 1 RP/RPo | Honeycomb Layer 2 RP/RPo | Honeycomb Layer 3 RP/RPo | Reactor RP/RPo |
| 5/11/2005 | 11570 | 0.55 | 0.61 | 0.71 | 0.62 |
| 6/9/2005 | 12266 | 0.48 | 0.62 | 0.75 | 0.61 |
| 7/12/2005 | 13058 | 0.49 | 0.57 | 0.73 | 0.59 |
| 7/13/2005 | 13082 | 0.47 | 0.60 | 0.70 | 0.59 |
| 8/10/2005 | 13754 | 0.47 | 0.60 | 0.75 | 0.61 |
| 8/11/2005 | 13778 | 0.45 | 0.54 | 0.72 | 0.57 |
| 8/31/2005 | 14258 | 0.45 | 0.55 | 0.68 | 0.56 |
| 9/1/2005 | 14282 | 0.45 | 0.54 | 0.69 | 0.56 |
| 9/28/2005 | 14930 | 0.44 | 0.54 | 0.68 | 0.55 |
| 9/29/2005 | 14954 | 0.43 | 0.54 | 0.67 | 0.55 |

Figure 4-3 presents the Reactor Potential results for the individual catalyst layers, as well as for the entire reactor overall. As would be expected, the results indicate the Reactor Potential for first layer is the lowest, and the potential for the third layer is the highest. While the results for each catalyst layer exhibit some scatter, the trends for each layer are clear. All three layers show an obvious decline in Reactor Potential over the course of the 2005 ozone season. On an overall basis, the results show the potential for the entire reactor decreased from nominally 0.62 to 0.55 during the five-month test period. This ending Reactor Potential number (55% of the value when new) may seem low considering SCR vendors generally define end-of-life for the catalyst as $K/K_0$ (or sometimes $RP/RP_0$) equal to 0.60 or 0.65. However, it is interesting to note that Southern Company chose to add the new fourth layer of catalyst to the Gorgas Unit 10 reactor during the outage between the 2005 and 2006 ozone seasons. This decision was not based on the *in situ* measurements, but rather based on the results of the annual third-party

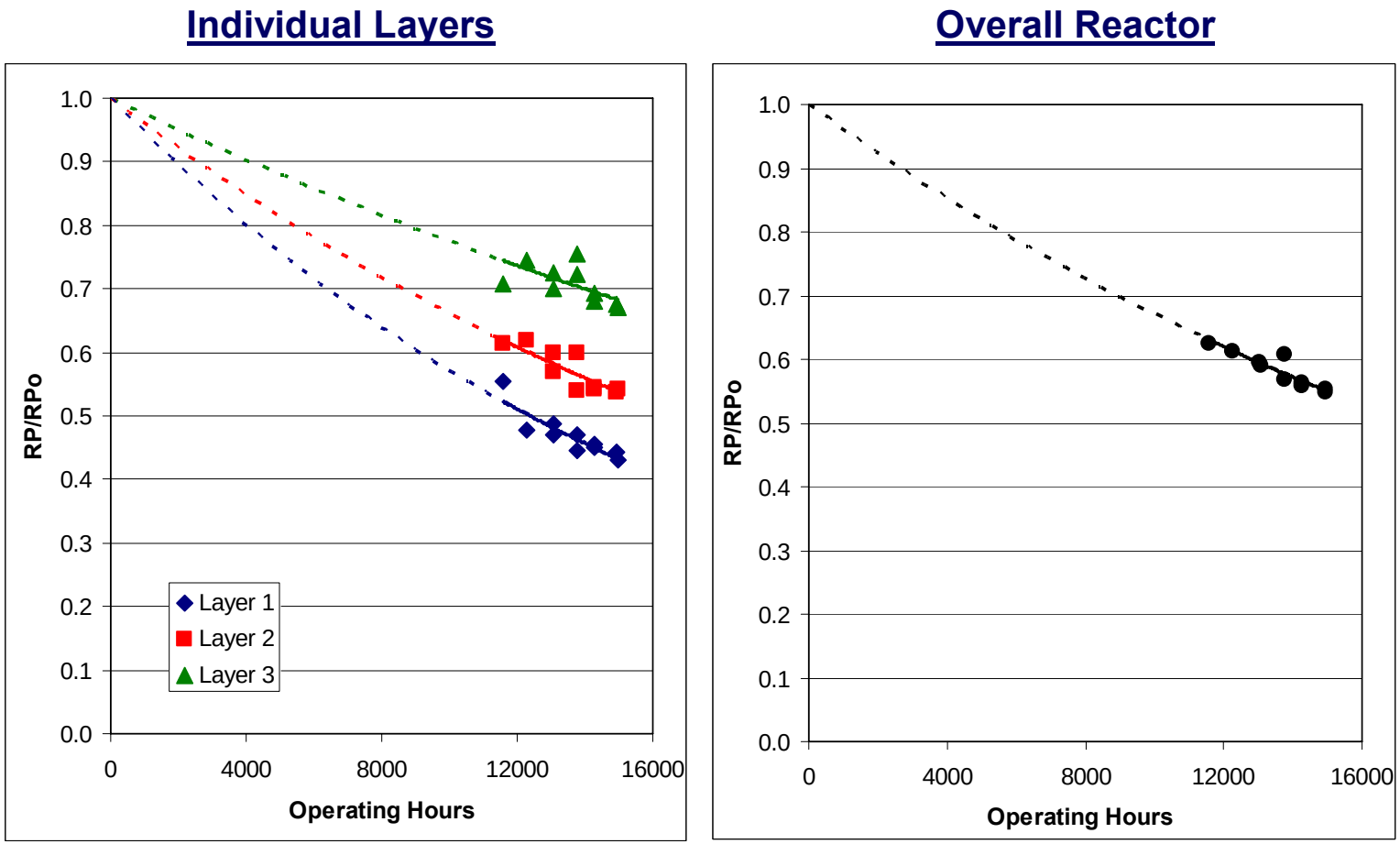



**Figure 4-3. Summary of *In situ* Reactor Potential Results for 2005**

analysis of physical catalyst samples removed from the reactor. The results of these third-party analyses will be discussed, as well as compared to the *in situ* results, in Section 5.

## 4.3 2006 Ozone Season *In situ* Test Results

A number of changes, to both the Gorgas Unit 10 SCR and the *in situ* activity system, were made between the 2005 and 2006 ozone seasons.

A. Gorgas SCR System

As discussed in Section 3, after the 2005 ozone season the first layer of honeycomb catalyst was removed from both Gorgas Unit 10 SCR reactors (Reactor A and Reactor B). New layers of plate type catalyst was installed in Layers 1. In addition the used catalyst from Layers 1 of the A and B Reactors was then installed as the fourth layer; however, Layer 1 from the A reactor was installed as the fourth layer in the B Reactor and vice versa (see Figure 3-1). Recall the *in situ* activity devices are installed in the B Reactor.

B. *In situ* Activity System

As mentioned previously, the ammonia delivery, $NO_x/O_2$ analysis and valve switching systems were all upgraded between the 2005 and 2006 ozone seasons. In addition, additional test modules were added to the B Reactor. During the proof-of-concept tests during the 2005 ozone season there was a single *in situ* test module installed on each of the three filled layers. For the 2006 ozone season, an additional test module was added to Layers 1, 2, and 3 and two modules were added to the spare Layer 4 (which was filled with the used catalyst from Layer 1). This is shown schematically in Figure 4-4.

Before discussing the *in situ* results from the 2006 ozone season tests, two issues need to be addressed that impacted some of the results. The first issue deals with the test modules added to the fourth layer. For Layers 1 to 3, physical access to the underside of the layer allowed the outlet sample probes on each layer to be located within 150 mm (6 inches) of the outlet of the catalyst material. For the fourth layer, the lack of physical access and placement of structural steel around the perimeter of the reactor meant that the outlet probe from the two *in situ* modules on Layer 4 were nominally 1.8 meters (6 feet) from the catalyst exit. To locate the Layer 4 outlet probe closer to the catalyst would have required installing scaffolding inside the SCR reactor at the outlet of Layer 4. This was beyond the scope of the project. In addition, the probe was located in the sloped hopper region which impacted the gas flow path causing additional flow issues in terms of sampling the gas treated with the supplemental ammonia. As will be seen, mixing between the catalyst exit and the Layer 4 sample probe compromised these measurements.

The second issue was sootblower operation. There are three sootblowers installed per layer in each SCR reactor. Figure 4-5 shows these sootblowers relative to the *in situ* modules. For a large portion of the ozone season the sootblowers above the 1B, 2B, and 3B modules were not in service. As will be seen, this resulted in 1) a rapid decrease in the Reactor Potential measured for each layer due to deposition and 2) caused a flow maldistribution within the reactor that compromised the *in situ* measurements on the “B” side.

C. Results

The results from the *in situ* tests during the 2006 ozone season will be discussed in the following sequence:

- Tests on the new Layer 1 plate catalyst
- Sampling issues due to the inability to locate the Layer 4 exit sampling probes close to the catalyst exit
- Impact of having sootblowers out-of-service for from 66 to 98 days on the results from some of the test locations
- Overall results for 2006

Initial Plate Catalyst Results

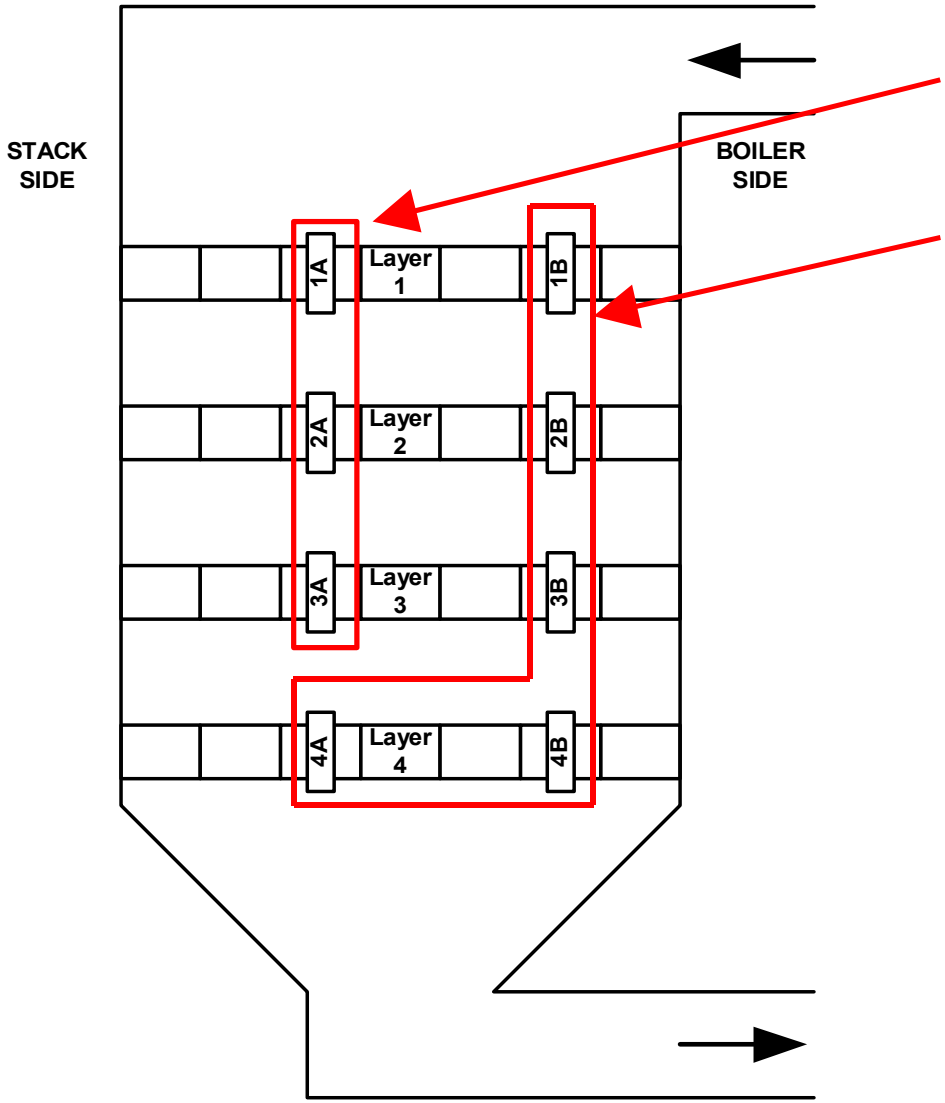
The installation of the new layer of plate catalyst to Layer 1 provided a good opportunity to quantitatively compare the *in situ* activity measurements to 1) the activity provided by the catalyst vendor and 2) an activity test by Southern Company's third-party catalyst tester who tested an unused sample of catalyst. After installation of the new plate catalyst in Layer 1, the SCR reactor was put into service on May 1, 2006. The initial *in situ* measurement of the first layer was made on May 5, 2006, which represents approximately 120 hours of operation on the new catalyst.

The measured activity is compared to that reported by the catalyst vendor and third-party catalyst test laboratory in Figure 4-6. Because Southern Company considers the absolute value of activity to be proprietary, the activities in Figure 4-6 have been normalized to the activity reported by the catalyst vendor. As can be seen in Figure 4-6, the absolute *in situ* activity measurements of the new plate catalyst are in excellent agreement with the vendor's value of activity and the third-party laboratory's measurements. The *in situ* measurements were 6% higher than the value from the vendor while the third-party laboratory's value was 3% lower than the vendor's reported activity. For the *in situ* determination, this is considered excellent agreement considering that the *in situ* determination needs to factor in the actual flue gas flow rate in order to determine the area velocity and then the activity. Further, the *in situ* measurement is made at an $NH_3/NO_x$ ratio > 1, whereas the vendor and third-party laboratory perform their laboratory measurements at $NH_3/NO_x = 1$ per the VGB Guidelines (VGB1998). This difference would tend to bias the *in situ* measurement slightly high.

4th Layer Results

As mentioned above, the exit sampling probes on the Layer 4 *in situ* modules were located within the sloped hopper region at the SCR exit 1.8 meters (6 ft) from the exit of the catalyst. Given this distance and the gas flow impacts of the sloped hopper, it was anticipated that this would not be an ideal situation.

Figures 4-7 and 4-8 present the results of the initial set of 2006 measurements for the two Layer 4 test locations. For comparison, the results from Layer 1 to 3 are also included in each figure. Figure 4-7 shows the results from the *in situ* modules on the "A" side of the reactor (i.e. the stack side of the reactor as shown in Figure 4-4). In this figure the measured $NO_x$ reduction is shown as a function of the supplementary ammonia injection rate ($NH_3/NO_x$ injected). As discussed in the presentation of the results for the 2005 ozone season, the $NO_x$ reduction is expected to increase and then flatten out at a maximum level when the local $NH_3/NO_x$ ratio




- **Test locations 1A, 2A and 3A were those utilized during the 2005 ozone season**
- **Locations 4A and 1B through 4B were added prior to the 2006 ozone season**

**Figure 4-4. B Reactor *In situ* Modules 2005 and 2006 Ozone Seasons**

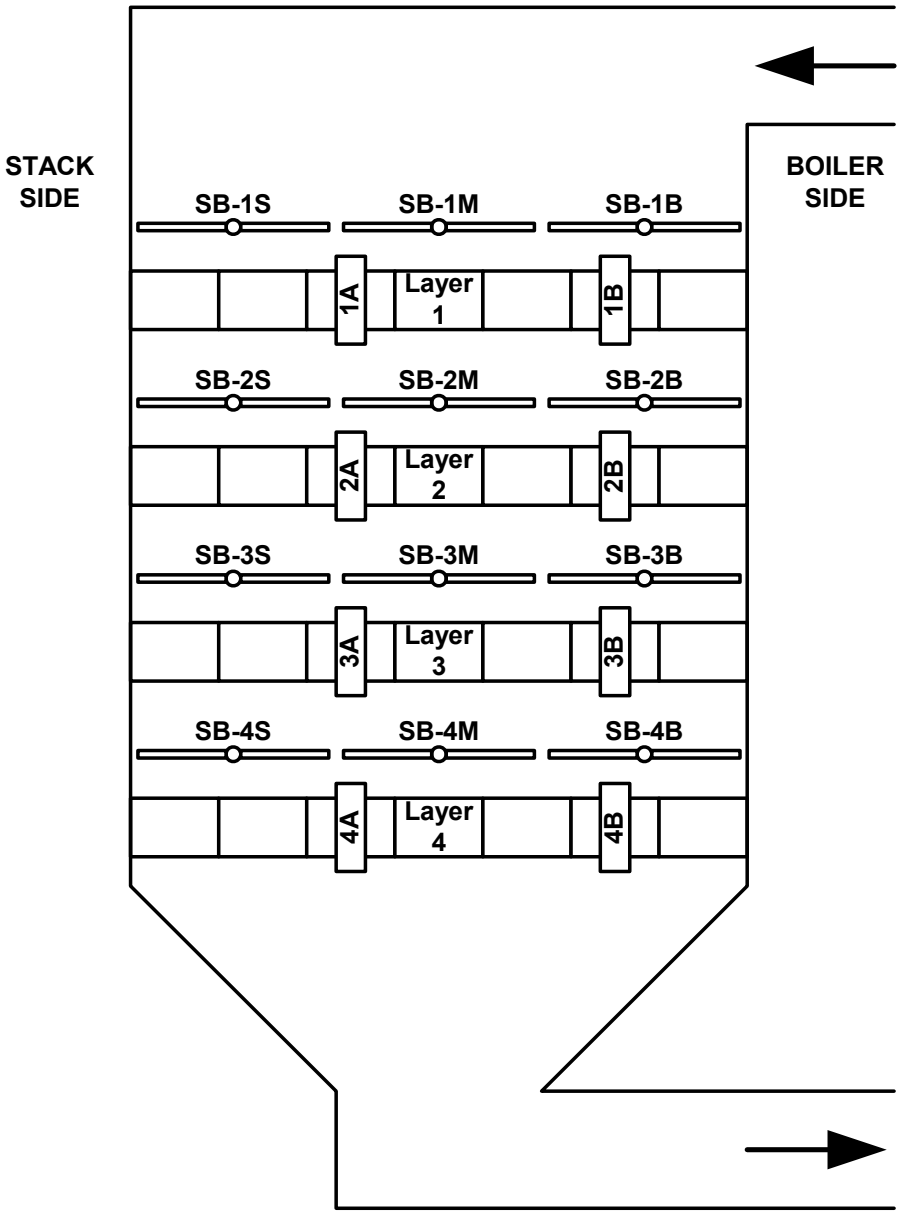



**Figure 4-5. B-Reactor Sootblower Configuration**

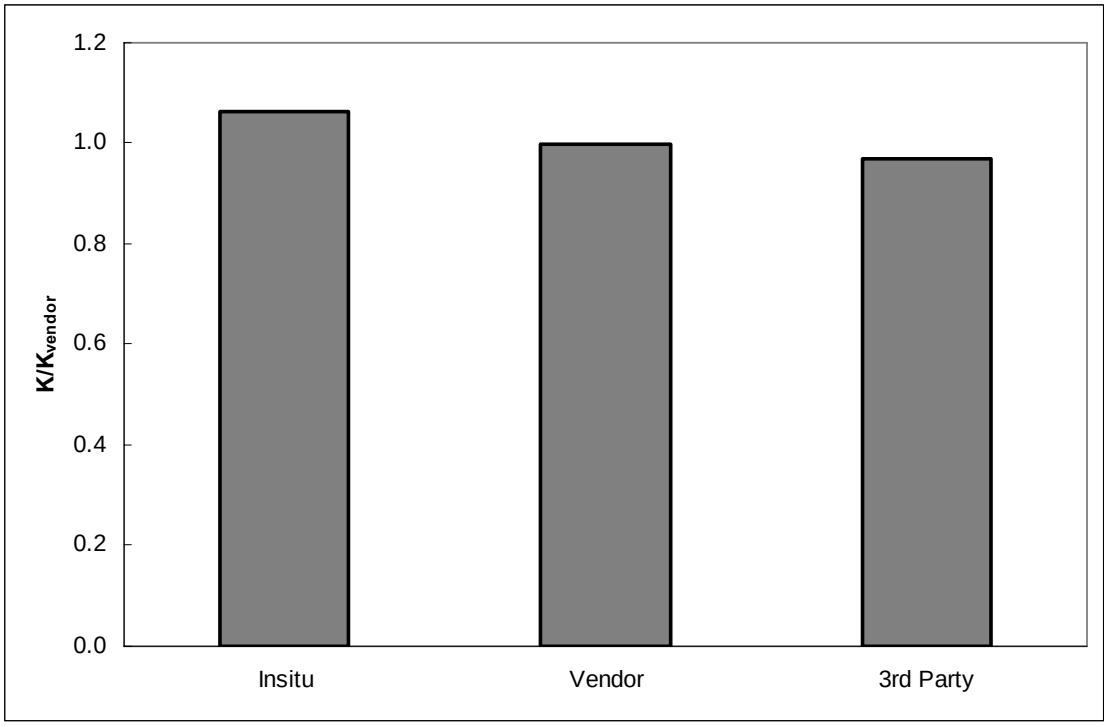



**Figure 4-6. Measured Activity of New Plate Catalyst**

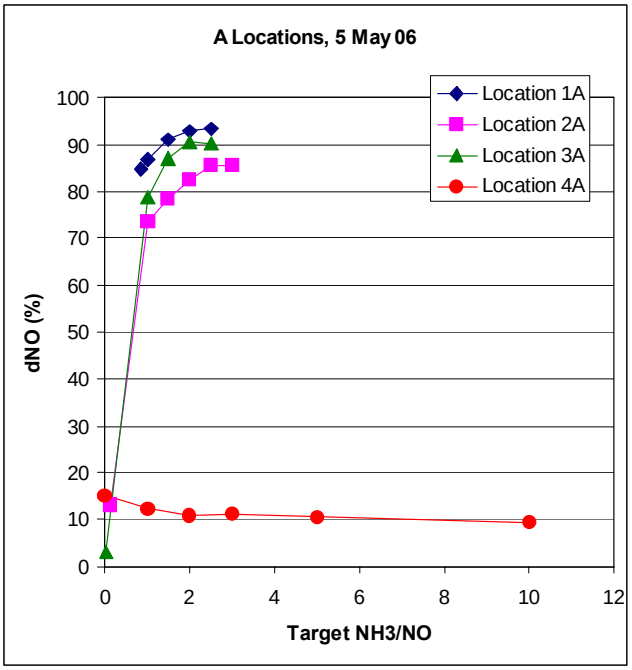



**Figure 4-7. Initial *In situ* Measurements on the "A" Side Modules During the 2006 Ozone Season (note, poor results for Layer 4)**

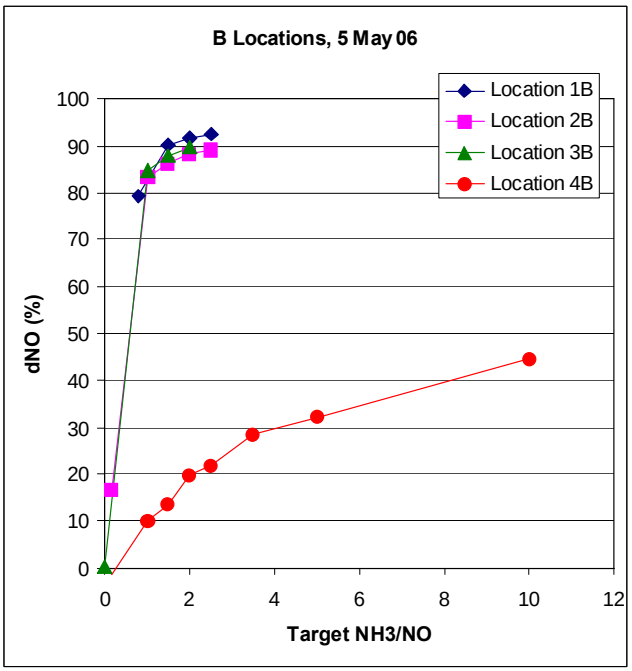



**Figure 4-8. Initial *In situ* Measurements on the "B" Side Modules During the 2006 Ozone Season (note, poor results for Layer 4)**

increases above one. As can be seen in Figure 4-7, this occurs for the *in situ* modules on Layers 1, 2, and 3, but not for Layer 4. While the overall $NO_x$ reduction for Layer 4 was expected to be lower than the other layers (since it was the used Layer 1 catalyst from the other Gorgas 10 SCR reactor) the measurements showed essentially no effect on the $NO_x$ reduction as the supplemental ammonia injection rate was increased. Clearly the Layer 4 exit sampling probe was not sampling flue gas that was treated with the supplemental ammonia. Figure 4-8 shows the results of comparable measurements for the *in situ* modules on the "B" side of the reactor (i.e. the boiler side of the reactor as shown in Figure 4-4). For the *in situ* module on the B side of Layer 4 some increase in $NO_x$ reduction is noted with the injection of supplemental ammonia. But, like the "A" side module, clearly the exit probe was not sampling the treated gas. Given these results, *in situ* activity measurements could not be made on Layer 4.

Out-of-service Sootblower Effects

Figure 4-5 shows how the three sootblowers on each level are oriented relative to the *in situ* modules. For convenience the sootblowers are referred to as S (stack), M (middle), and B (boiler); note, this is not the plant's designation for the sootblowers. Figure 4-9 plots the number of days each sootblower was out-of-service during the 2006 ozone season. As can be seen, the sootblowers on the boiler side of the reactor were out-of-service for about 50% of the five-month ozone season. The results presented below will show this had an impact on the *in situ* results.

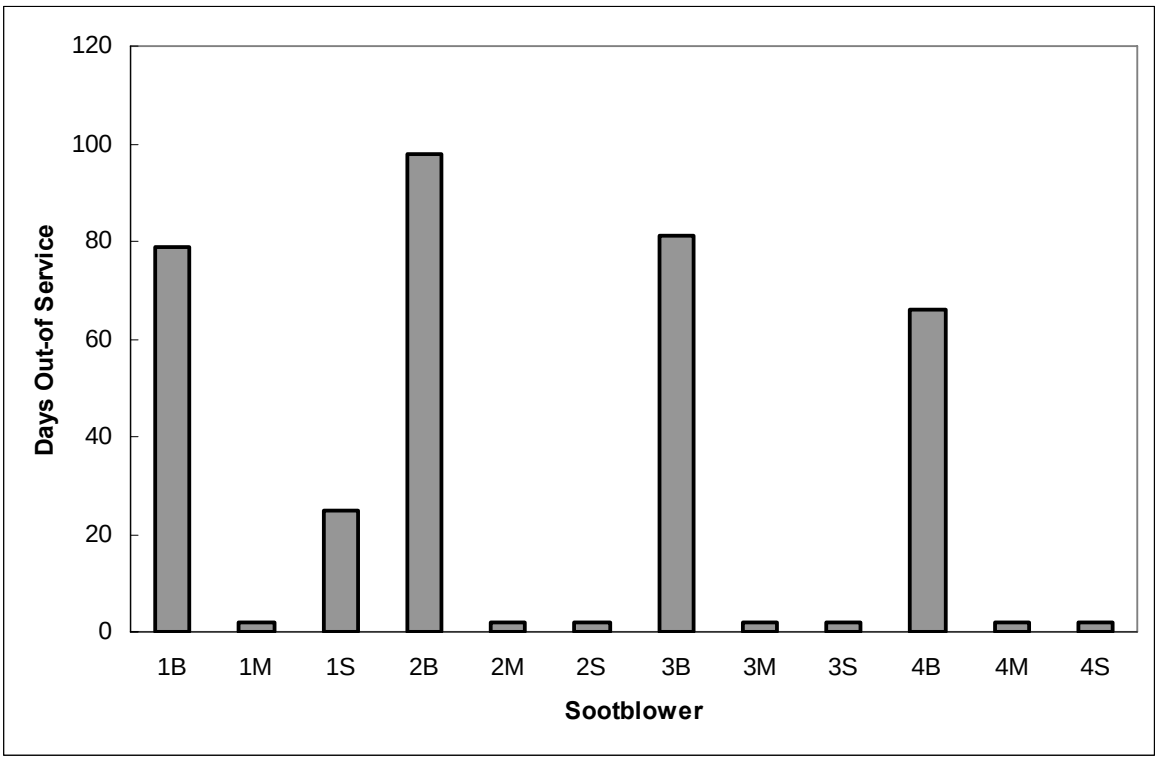



**Figure 4-9. 2006 Ozone Season Sootblower Out-of-Service Record**

The test protocol shown in Figure 4-1 was followed during the 2006 ozone season. At each of the *in situ* modules the supplemental ammonia was incrementally increased and the $NO_x$ reduction measured. The results for the "A" and "B" modules for Layers 1, 2 and 3 are shown in Figure 4-10 and 4-11, respectively. For the "A" side modules, the following observations can be made:

Layer 1 (A module): Figure 4-10a

Other than overall ash buildup, which increases the area velocity (and reduces the Reactor Potential) of the catalyst layer, the *in situ* measurements are basically not impacted by the sootblowers being out-of-service. For each set of individual tests, with increasing injection of supplemental ammonia the $NO_x$ reduction increases and levels out. The interesting point to be noted in Figure 4-10a is that while the tests from May 5, 2006 to August 2, 2006 show a steady decline in maximum $NO_x$ removal (i.e. Reactor Potential), the tests on August 31, 2006 and September 27, 2006 both indicate an increase in maximum $NO_x$ removal. A review of plant operating records showed that most of the sootblowers were returned to service during the time period between August 2$^{nd}$ and 31$^{st}$. The increase in $NO_x$ removal after this time is notable for two reasons. First, it indicates the lack of sootblowing prior to that time resulted in ash deposition on other areas of the catalyst layer that reduced the available surface area, increased the area velocity through the layer overall, and resulted in a decreased maximum $NO_x$ removal, or Reactor Potential. Second, it also indicated that once the sootblowers were returned to service, they were able to remove some of the accumulated ash build-up, thus decreasing the area velocity, and allowing the $NO_x$ reduction, or Reactor Potential to increase.

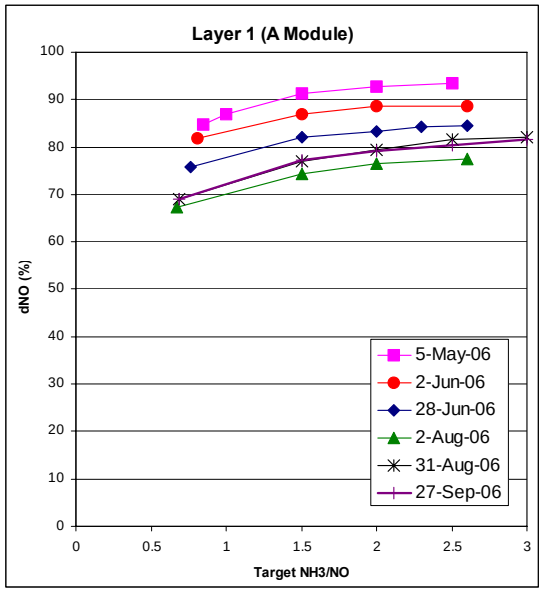
Layer 2 (A module): Figure 4-10b

Similar to the Layer 1A module, this module was not directly impacted by the sootblowers being out-of-service in terms of providing data upon which to extract an *in situ* Reactor Potential. Again, for each individual set of tests, with increasing ammonia injection, the $NO_x$ reduction eventually levels out. The decrease in $NO_x$ reduction, up to August 2, 2006, as well as the increase in $NO_x$ reduction after August 2, 2006, are both markedly larger than those seen for Layer 1 (see Figure 4-10b). This indicates a much larger buildup of ash occurred on Layer 2 than had occurred than on Layer 1 during the time the sootblowers were out-of-service.

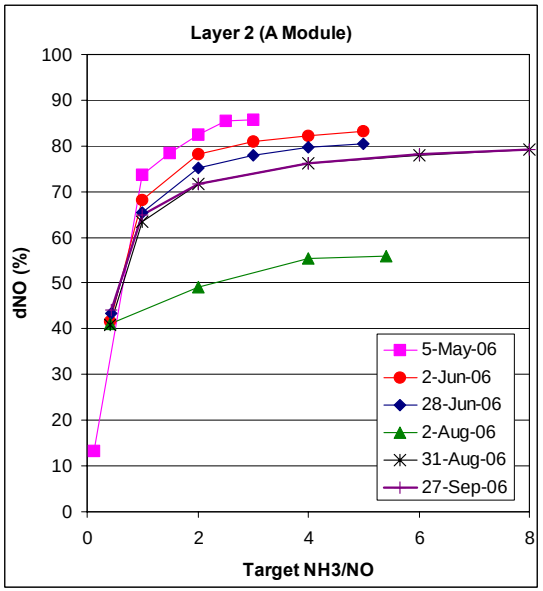
Layer 3 (A module): Figure 4-10c

The A module on Layer 3 was directly impacted by the buildup of fly ash. As can be seen in Figure 4-10c, for the test on August 2, 2006, the $NO_x$ reduction never leveled off with increasing supplemental ammonia injection. This indicates the flue gas being sampled at that location had not reached a point where the $NH_3/NO_x$ ratio was greater than 1.0. Thus, for this test a valid *in situ* Catalyst Activity measurement cannot be extracted from the data. However, as was seen for both the Layer 1A and 2A modules, once the sootblowers were put back in service, Figure 4-10c shows both a return to the $NO_x$ reduction characteristic that was expected as well as a marked increase in $NO_x$ reduction.

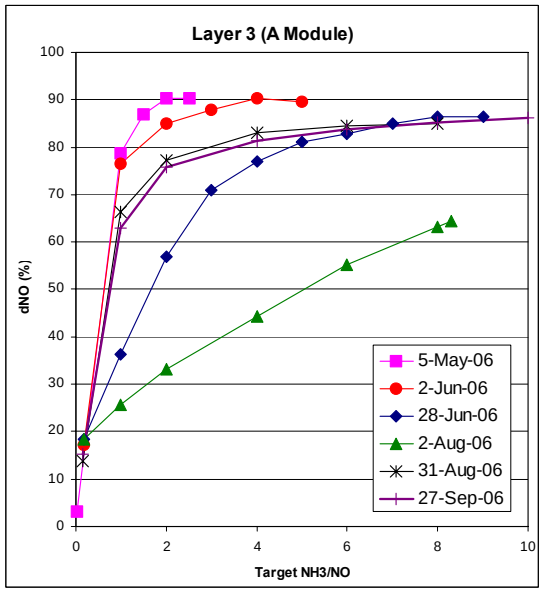
With respect to being directly impacted by fly ash build-up, the "B" modules located in the vicinity of the boiler side sootblowers did not fare as well as the "A" modules, as shown in Figure 4-11.




(a) Layer 1

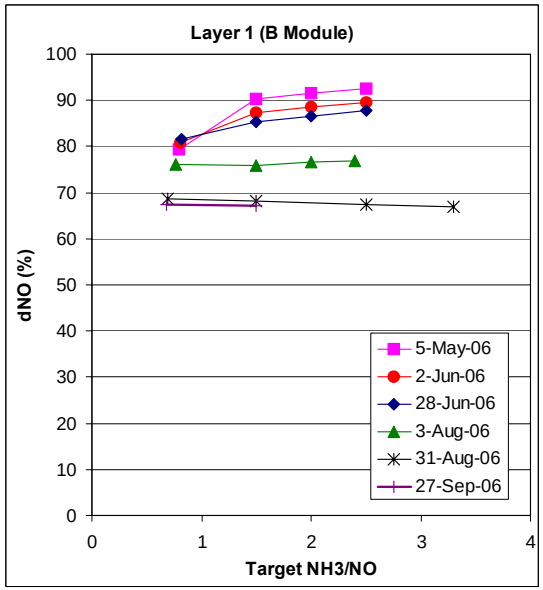



(b) Layer 2

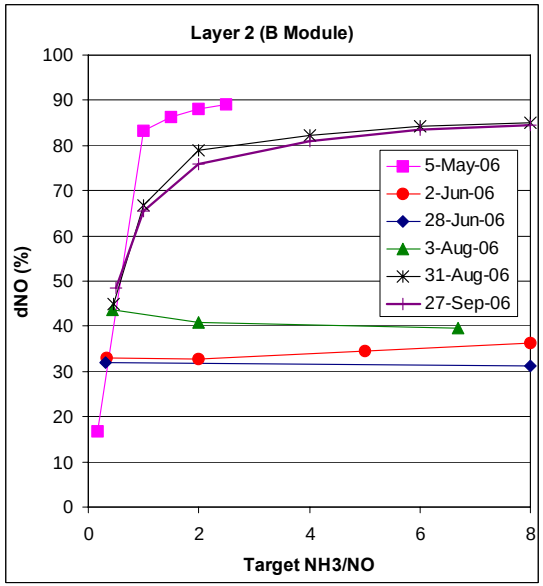



(c) Layer 3

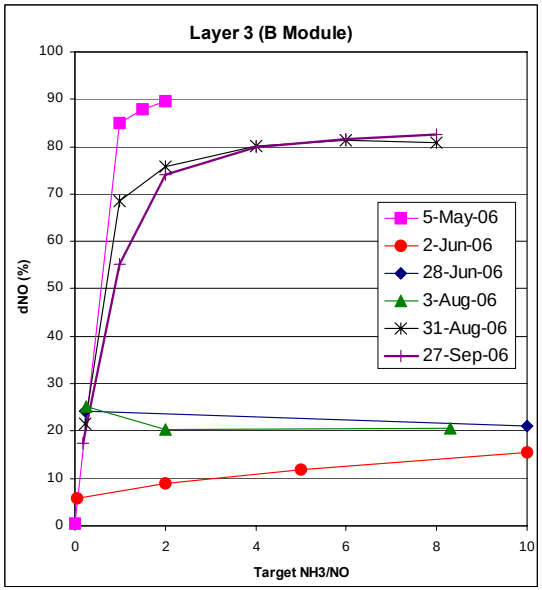
**Figure 4-10. 2006 Test Data; A Locations**




(a) Layer 1




(b) Layer 2




(c) Layer 3

**Figure 4-11. 2006 Test Data; B Locations**

Layer 1 (B module): Figure 4-11a

Figure 4-11a indicates that while the data through June 28, 2006 shows the expected $NO_x$ removal response to increasing supplemental ammonia injection, from August 3, 2006 onward, there was no response to increasing $NH_3/NO_x$ ratio. This indicates the flue gas being sampled at the outlet of the module has not been treated by the supplemental ammonia.

Layer 2 (B module): Figure 4-11b

After the first test on May 5, 2006, ash deposition resulting from the sootblowers being out-of-service had altered the gas flow patterns near the Layer 2 B module to the point of rendering the data for the next three tests useless (tests on 6/2/06, 6/28/06, and 8/3/06). However, with the sootblowers back in service, the data on August 31, 2006 and September 27, 2006 returned to exhibit the expected $NO_x$ reduction characteristic, as well as a large increase in $NO_x$ reduction with supplemental ammonia injection.

Layer 3 (B module): Figure 4-11c

As can be seen in Figure 4-11c, the overall trends for Module 3B were the same as those for module 2B. Namely, after the first test of the Layer 3B module on May 5, 2006, the sootblowers being out-of-service rendered the remaining data for the next three sets of tests useless in terms of extracting *in situ* Catalyst Activity information. However, once the sootblowers returned to service, the expected $NO_x$ removal characteristics returned, and *in situ* activity determinations were possible.

Due to the sootblowers being out-of-service for so long, some of the *in situ* activity measurements were compromised. Ash deposition in the reactor must have been substantial enough to alter the gas flow patterns within the reactor. As a consequence of these altered gas flow patterns, the outlet *in situ* gas sampling probes no longer sampled flue gas that was treated with the supplemental ammonia and should have entered the catalyst directly above the sampling probe.

Overall 2006 Ozone Season Results

Based on the previous discussion, nearly all of the data from the A-side (stack-side) *in situ* modules produced valid *in situ* data. However, many of the tests of the B-side (boiler-side) modules did not produce valid *in situ* data due to the sootblowers being out-of-service. Table 4-2 summarizes the *In situ* data collected during the 2006 ozone season for both the A-side and B-side test modules. While a direct comparison of the A-side and B-side test results for the same catalyst layer may be made in only a few cases, the results indicate that there can be significant differences in Reactor Potential values measured across a single catalyst layer.

The relative Reactor Potential measured for both the 2005 and 2006 ozone seasons are shown for Layer 1 in Figure 4-12 and for Layers 2 and 3 in Figure 4-13. In these two figures the open symbols represent data from the 2005 ozone season and the solid symbols represent data from the 2006 ozone season. It should also be noted that the 2006 data plotted is from the A-side test modules only, in order to provide the best basis of comparison for the 2005 data.

**Table 4-2. *In situ* Results: 2006 Ozone Season**

| 2006 Ozone Season Insitu Data: A locations | | | | | |
|---|---|---|---|---|---|
| Test Date | Operating Hours | Plate Layer 1 RP/RPo(1) | Honeycomb Layer 2 RP/RPo | Honeycomb Layer 3 RP/RPo | Reactor RP/RPo |
| 5/5/2006 | 15098 | 0.89 | 0.63 | 0.77 | 0.76 |
| 6/2/2006 | 15770 | 0.71 | 0.58 | 0.74 | 0.68 |
| 6/28/2006 | 16394 | 0.61 | 0.53 | 0.65 | 0.60 |
| 8/2/2006 | 17234 | 0.49 | 0.27 | | |
| 8/31/2006 | 17930 | 0.56 | 0.51 | 0.62 | 0.56 |
| 9/27/2006 | 18578 | 0.55 | 0.51 | 0.65 | 0.57 |

| 2006 Ozone Season Insitu Data: B locations | | | | | |
|---|---|---|---|---|---|
| Test Date | Operating Hours | Plate Layer 1 RP/RPo(1) | Honeycomb Layer 2 RP/RPo | Honeycomb Layer 3 RP/RPo | Reactor RP/RPo |
| 5/5/2006 | 15098 | 0.85 | 0.72 | 0.74 | 0.77 |
| 6/2/2006 | 15770 | 0.74 | | | |
| 6/28/2006 | 16394 | 0.69 | | | |
| 8/2/2006 | 17234 | | | | |
| 8/31/2006 | 17930 | | 0.62 | 0.54 | |
| 9/27/2006 | 18578 | | 0.61 | 0.57 | |

(1) RPo based on the original honeycomb catalyst

For Layer 1 at the end of the 2005 ozone season, the relative Reactor Potential of the layer had decreased to nominally $RP/RP_o = 0.43$. With the exchange of the honeycomb catalyst in the first layer with new plate catalyst at the start of the 2006 ozone season the relative Reactor Potential increased to 0.89. However, a rapid drop in the Layer 1 Reactor Potential occurred during the first four tests in 2006 from 0.89 to 0.49. This was a consequence of the sootblowers being out-of-service. When the sootblowers were put back in service, the relative Reactor Potential increased to 0.56 as some of the blockage was removed.

The 2006 relative Reactor Potential results for Layers 2 and 3 are shown in Figure 4-13. Two things are noteworthy this figure. First, relative to the end of the 2005 ozone season, the relative Reactor Potential of Layers 2 and 3 had increased at the beginning of 2006. This is likely due to cleaning of the reactor and vacuuming of the catalyst surface following the end of the 2005 ozone season. Since the relative Reactor Potentials for both layers were nearly the same at the beginning of 2006 as they were at the beginning of 2005, this indicates that most of the decrease in Reactor Potential during the 2005 ozone season was due to blockage, rather than catalyst deactivation. Second, as with Layer 1, the Layer 2 results indicate there was a large decrease in Reactor Potential during the first four tests in 2006 due to the sootblowers being out-of-service. During this time, the relative Reactor Potential fell from 0.63 to 0.27. However, when the sootblowers were put into service, the value increased to 0.51 and leveled out. Layer 3 shows the same general trends as Layers 1 and 2, but without the large decrease corresponding to the August 2, 2006 data point. As noted above, the Layer 3A test module did not yield valid data at this point in time.

The overall Reactor Potential for Layers 1, 2, and 3 are shown in Figure 4-14. Again, one sees an increase in Reactor Potential with the replacement of Layer 1 with the plate catalyst. This is then followed by a rapid decrease in Reactor Potential due to pluggage resulting from the out-of-service sootblowers.

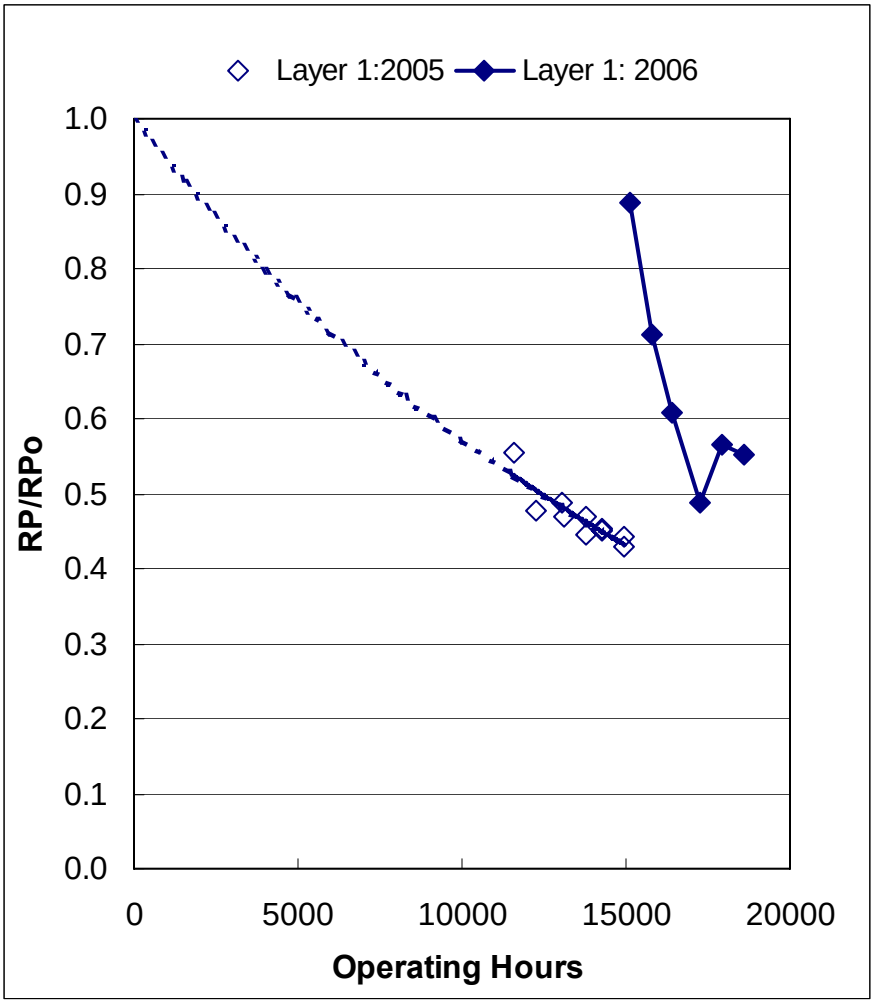



**Figure 4-12. *In situ* Reactor Potential Results – Layer 1 (2006 data is from A-side modules only)**

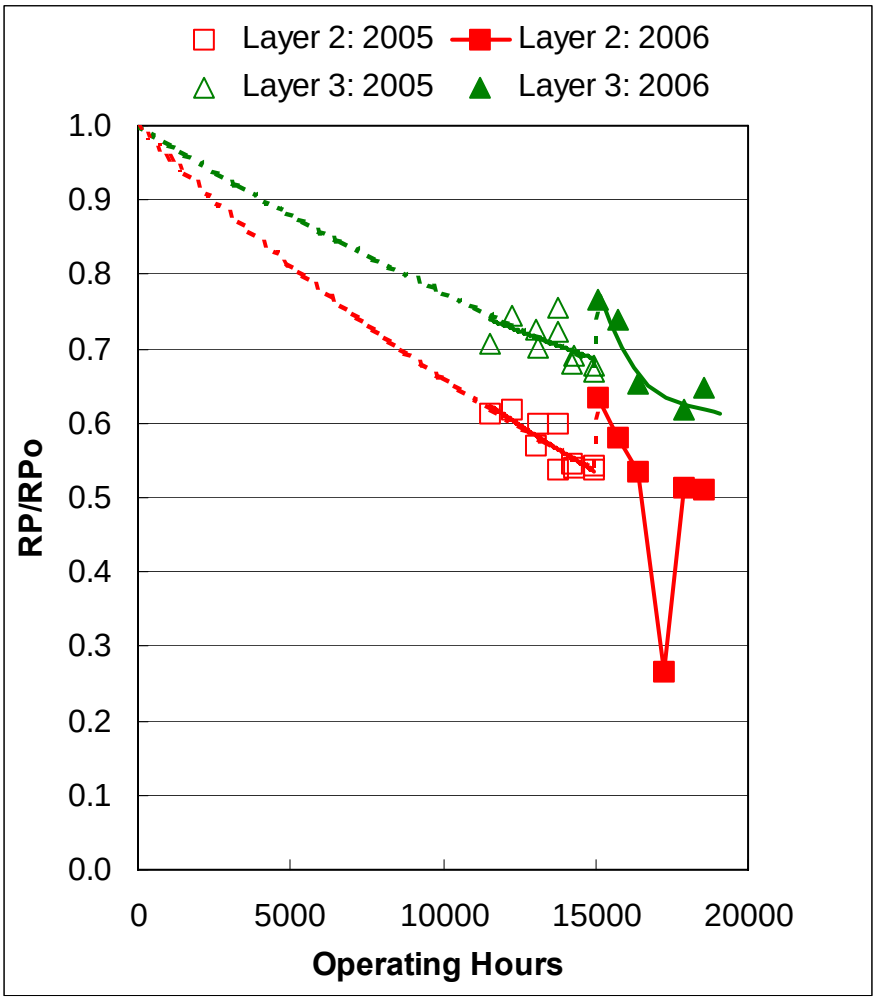



**Figure 4-13. *In situ* Reactor Potential Results – Layers 2 and 3 (2006 data is from A-side modules only)**

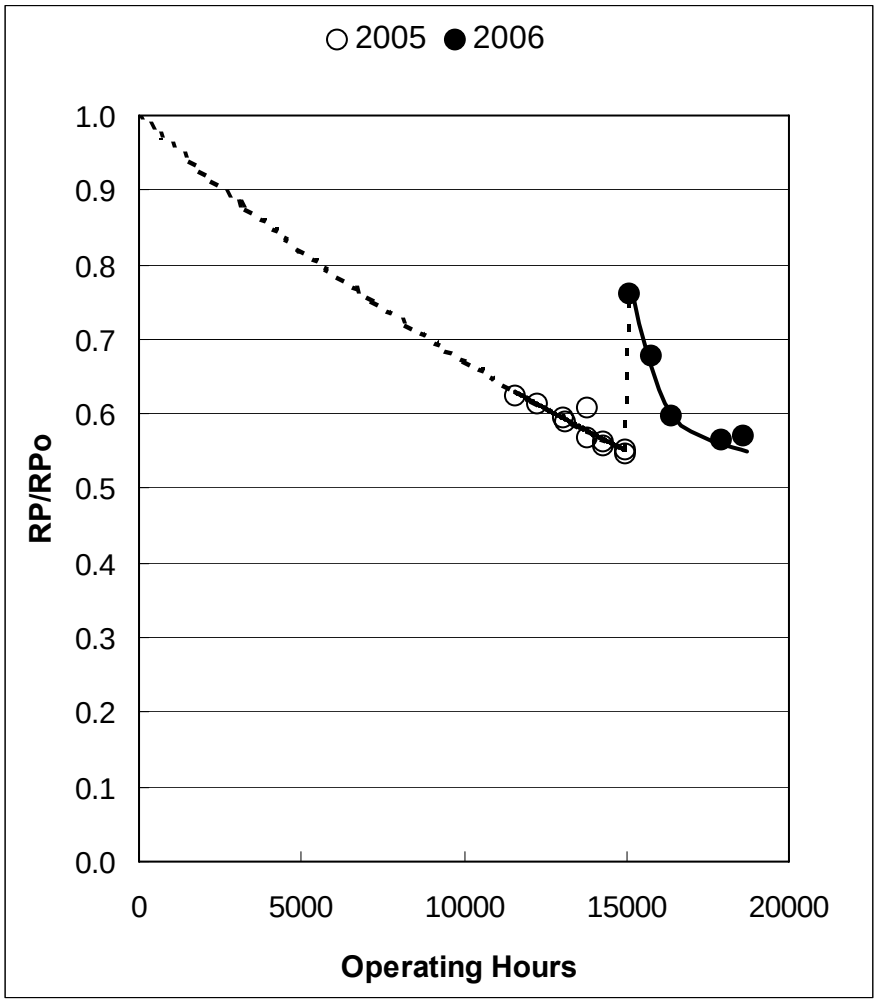



**Figure 4-14. *In situ* Reactor Potential Results – Overall Reactor (2006 data is from A-side modules only)**

# 5

# COMPARISON OF *IN SITU* AND LABORATORY TEST RESULTS

This section will compare the *in situ* activity results to the results obtained from laboratory analysis of samples taken from the reactor. The fact that there is good quantitative agreement between the laboratory and *in situ* measurements was already discussed in Section 4 in terms of the measured activity of the new plate catalyst installed in Layer 1 of the SCR reactor prior to the 2006 ozone season (see Figure 4-6). This section will focus not only on an absolute comparison of the *in situ* and laboratory activity results, but also discuss issues associated with determining the Reactor Potential. This is important because Reactor Potential is the quantity an SCR operator needs to track to effectively manage the catalyst life and replacement.

As mentioned in Section 2, an important part of a utility's catalyst management program is the removal of physical samples from the reactor, and their subsequent analysis by either the original catalyst vendor or a third-party testing organization. For Gorgas Unit 10, Southern Company personnel remove a test sample from each layer of catalyst in both reactors at the end of each ozone operating season. Generally, these samples are removed in October and are then sent to the third-party testing organization responsible for catalyst testing for all of Southern Company's SCR systems. The third-party laboratory performs the tests for Catalyst Activity using the protocol outlined in the VGB Guidelines (VGB, 1998), and reports the activity values as K (Nm/hr), or $K/K_o$.

To then determine the Reactor Potential, the amount of catalyst blockage by ash needs to be assessed. The Reactor Potential of the $i^{th}$ layer can then be calculated from equation (2-10).

$$RP_i = \frac{K_i\,(1 - B_i)}{A_{vi}^{clean}} \qquad (5\text{-}1)$$

$RP_i$ = Reactor Potential of the $i^{th}$ layer

$K_i$ = Catalyst Activity of the $i^{th}$ layer

$B_i$ = Fractional blockage of the $i^{th}$ layer

$A_{vi}^{clean}$ = Area velocity of the $i^{th}$ layer for clean conditions

As discussed previously, the *in situ* device makes a direct measurement of Reactor Potential. To compare the Catalyst Activity values, $K_i$, the above equation can be rearranged and the area velocity and blockage used to calculate the activity from the measured Reactor Potential.

There are two approaches that can be used to determine the blockage. The first is a visual inspection of the reactor at the end of the ozone season. The drawbacks of this approach are 1) it is somewhat qualitative and primarily assesses the ash layer on the surface of the catalyst and 2) there is always the question as to whether the observed deposits were present during operation or fell from turning vanes and beams during the reactor shutdown process.

The second approach is to calculate the blockage from the measured pressure drop across the layer. Ignoring the inlet and outlet losses as the flue gas enters and exits a catalyst channel (which is a function of the velocity squared), the pressure drop varies linearly with the velocity in the channel due to the laminar flow through the catalyst channel. This leads to the following relationship between pressure drop and blockage.

$$B_i\ (\%) = 100\left(1-\frac{\Delta P_{cleani}}{\Delta P_i}\right),$$

$\Delta P_{cleani}$ = pressure drop without blockage across Layer i

$\Delta P_i$ = pressure drop with blockage across Layer i

$B_i$ = blockage across Layer i

Southern Company historically performs visual inspections for catalyst blockage. For this study both the visual assessment of blockage and the blockage calculated from the pressure drop are used to compare the *in situ* and laboratory results.

The comparison of the *in situ* and Laboratory results will be discussed in two subsections. First, the comparison will be made for the new layer of plate catalyst installed prior to the 2006 ozone season, by analyzing data collected just after installation and startup. Second, the comparison between the laboratory and *in situ* results for the layers of catalyst that have been in operation since 2002 will be discussed. This latter discussion will primarily be aimed at illustrating the importance of blockage on the results.

New Layer of Plate Catalyst

As discussed in Section 4, the installation of the new plate catalyst in Layer 1 provided a good opportunity to compare the *in situ* results to a laboratory determination of activity without having to deal with the issue of blockage. In this case, the *in situ* results can be compared to the activity provided by the catalyst supplier, and to the activity measured by Southern Company's third-party laboratory. The *in situ* measurements were made after approximately 120 hours of operation of the new catalyst.

The measured relative activities are shown in Table 5-1 and Figure 5-1. Because Southern Company considers the absolute value of activity to be proprietary, the activities in Figure 5-1 have been normalized to the activity reported by the catalyst vendor. As can be seen in Table 5-1 and Figure 5-1, the absolute *in situ* measurements of the new plate Catalyst Activity is in excellent agreement with the vendor's value of activity, and the third-party laboratory's measurements. The *in situ* measurements were 6% higher than the value from the vendor, while the third-party laboratory's value was 3% lower than the vendor's reported activity. For the *in situ* determination, this is considered excellent agreement considering that the *in situ* determination needs to factor in the actual flue gas flow rate in order to determine the area velocity and then the activity. Further, the *in situ* measurement is made at an $NH_3/NO_x$ ratio > 1, whereas the vendor and third-party laboratory perform their laboratory measurements at $NH_3/NO_x$ = 1 per the VGB Guidelines (VGB, 1998). This difference would tend to bias the *in situ* measurement to a slightly higher value.

**Table 5-1. New Plate Catalyst Measured Activity**

| Source | $K/K_{vendor}$ |
|---|---|
| Catalyst Vendor | 1 |
| Insitu | 1.06 |
| 3rd Party Laboratory | 0.97 |

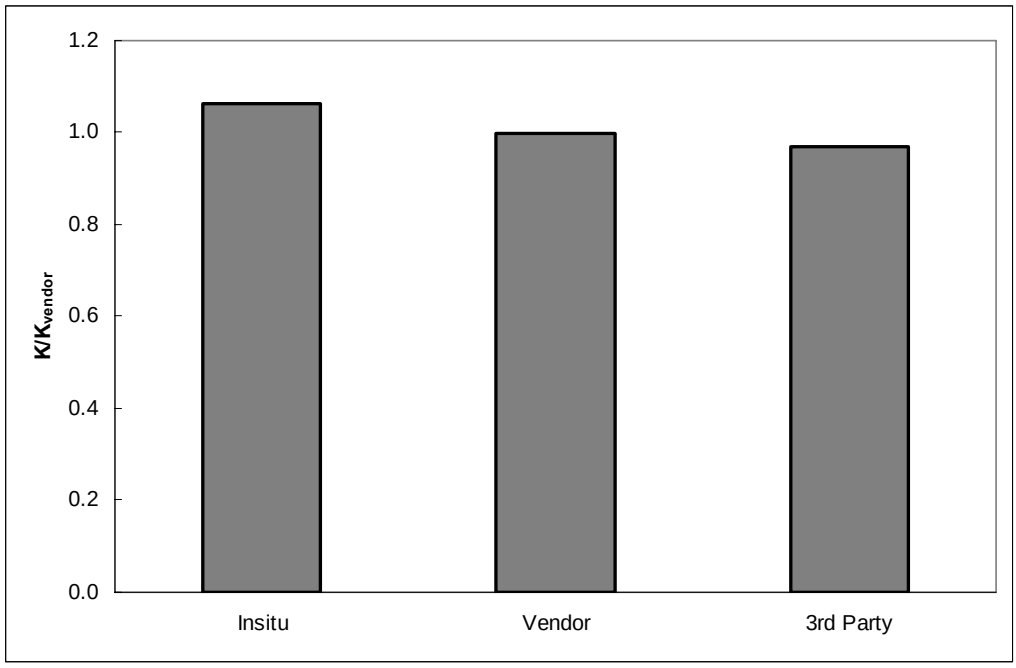



**Figure 5-1. New Plate Catalyst Measured Activity**

These results clearly validate the *in situ* approach to determining activity.

Older Honeycomb Catalyst Layers

This section will compare the *in situ* measurements to samples collected after the 2005 and 2006 ozone seasons and analyzed by Southern Company's third-party laboratory. This will include honeycomb samples from Layers 1, 2 and 3 in 2005; honeycomb samples from Layers 2 and 3 in 2006, and a sample of the new plate catalyst from Layer 1 that had operated through the 2006 ozone season.

To compare the laboratory and *in situ* results, in terms of either Activity or Reactor Potential requires that the blockage be assessed. Table 5-2 shows the blockage for the periods of interest based on both visual reactor inspections and pressure drop where available. As can be seen, there can be significant differences between the blockage calculated from the pressure drop across a layer and the visual estimate of blockage. For layers 2 and 3, the visual estimate of the blockage was always higher than that calculated from the pressure drop. The opposite is seen for the top layer for both the older honeycomb layer and the new plate catalyst.

**Table 5-2. Estimated Blockage**

| Date | Approximate Operating Hours | Layer 1 B (dP) % | Layer 1 B(Visual) % | Layer 2 B (dP) % | Layer 2 B(Visual) % | Layer 3 B (dP) % | Layer 3 B(Visual) % |
|---|---|---|---|---|---|---|---|
| Sep-05 | 14950 | 28.9 | 20 | 22 | 30 | (1) | 25 |
| May-06 | 0 | 0 (2) | 0 (2) | | | | |
| Sep-06 | 18578 | 9.8 (2) | 5.0 (2) | 23.2 | 36 | 16 | 32 |

(1) dP Transmitter Problem
(2) New Plate Catalyst

The blockage estimates shown in Table 5-2 were used along with the *in situ* measurements of Reactor Potential at the end of the 2005 and 2006 ozone seasons to calculate the relative activities, $K/K_o$. These in turn are compared to the laboratory activity measurements. These results are shown in Table 5-3.

Looking first at the latest samples from the end of the 2006 ozone season, one sees excellent agreement in $K/K_o$ between the laboratory determination of activity and the *in situ* measurements when the *in situ* Reactor Potential is corrected for blockage using the pressure drop measurements across the layers. For Layer 1 (new plate catalyst) and Layer 3, the $K/K_o$ values are identical between the two techniques. For Layer 2 the agreement is within 9%.

For the comparison after the 2005 ozone season, there was more variability. For Layer 1 the *in situ* value of $K/K_o$ based on the pressure drop measurements was 0.6 compared to 0.8 for the laboratory. For Layer 2, the visual $K/K_o$ value agreed well with the laboratory value and $K/K_o$ based on the pressure drop was within 13% of the laboratory value. For Layer 3, a pressure drop reading was not available at the end of the 2005 ozone season because of a transmitter problem. However, using the visual assessment of blockage, the *in situ* and laboratory $K/K_o$ values are in good agreement.

Overall there is very good quantitative agreement between the *in situ* measurements and the laboratory activity measurements. To compare these on a one-to-one basis requires a determination of the amount of blockage of the catalyst surface by ash. Conversely even if the laboratory measurements are used to determine Reactor Potential, the blockage needs to be determined. From the current results, calculating the blockage from a pressure drop measurement across each layer appears to better quantify the blockage than a visual assessment.

While there was good quantitative comparison between the *in situ* measurements and the laboratory measurements, it should also be noted that in the case of the laboratory measurement samples are only obtained once per year. The *in situ* device provides a much larger data set upon which to assess trends in deactivation, as shown previously in Figures 4-12 and 4-13.

**Table 5-3. $K/K_o$ Comparison; Laboratory and *In situ***

| Date | Approximate Operating Hours | Layer 1 | | | |
|---|---|---|---|---|---|
| | | RP/RPo Insitu | K/Ko (dP) Blockage Adjusted | K/Ko(Visual) Blockage Adjusted | 3rd Party Laboratory |
| Sep-05 | 14950 | 0.44 | 0.62 | 0.55 | 0.8 |
| May-06 | New Plate Catalyst | 1.00 | 1.00 (2) | | 1.00 (1) |
| Sep-06 | 18578 (3) | 0.62 (2) | 0.7 (2) | 0.67 (2) | 0.7 (1) |

(1) Relative to Third Party Laboratory's Ko Value
(2) Relative to the Insitu Plate Catalyst Measurement in May 2006
(3) 3624 hrs on the new plate catalyst

| Date | Approximate Operating Hours | Layer 2 | | | |
|---|---|---|---|---|---|
| | | RP/RPo Insitu | K/Ko (dP) Blockage Adjusted | K/Ko(Visual) Blockage Adjusted | 3rd Party Laboratory |
| Sep-05 | 14950 | 0.54 | 0.69 | 0.77 | 0.78 |
| Sep-06 | 18578 | 0.51 | 0.66 | 0.80 | 0.72 |

| Date | Approximate Operating Hours | Layer 3 | | | |
|---|---|---|---|---|---|
| | | RP/RPo Insitu | K/Ko (dP) Blockage Adjusted | K/Ko(Visual) Blockage Adjusted | 3rd Party Laboratory |
| Sep-05 | 14950 | 0.68 | N/A | 0.91 | 0.9 |
| Sep-06 | 18578 | 0.64 | 0.76 | 0.94 | 0.77 |

# 6

# CATALYST MANAGEMENT

## 6.1 Introduction

Determining Catalyst Activity, as discussed previously, is just the first step in catalyst management. After the Catalyst Activity is measured the information then is used to determine when catalyst additions, exchanges, or in-situ cleaning/regeneration are required. It should also be noted that effective catalyst management does not focus just on minimizing catalyst cost. Rather, effective catalyst management strives to minimize overall operating costs. For instance, taking a special outage to change a layer of catalyst when it reaches 'End-of-Life' may be more costly than changing catalyst during an earlier planned outage; even though this would result in essentially discarding some useful Catalyst Activity. Thus, it is important to factor planned outages into catalyst management decisions.

Catalyst management is usually performed with the aid of catalyst management software. Many of the catalyst vendors and SCR consultants have developed their own proprietary catalyst management software programs. In this section, the *in situ* activity measurements will be used with a catalyst management program developed by EPRI called CatReact™ to illustrate how these *in situ* measurements support catalyst management decisions.

## 6.2 CatReact™

CatReact™ is a software product developed by EPRI to help utilities make catalyst management decisions for their Selective Catalytic $NO_x$ Reduction (SCR) systems. The program determines when future catalyst additions or replacements will be necessary and calculates the operations and maintenance costs of the SCR system. Cost elements include 1) catalyst purchases, 2) labor to add or replace catalyst, 3) reagent usage, 4) fan power associated with the added pressure drop resulting from a) the additional catalyst and b) ash deposition resulting in blockage of the catalyst, 5) lost generation for an outage, and 6) purchasing $NO_x$ credits for periods when the $NO_x$ reduction is lower than the normal set point.

CatReact™ not only calculates replacement strategies based on the catalyst vendor's recommendations, but also allows the catalyst management decisions to be integrated with the utility's schedule of planned outages.

In a typical catalyst management plan, the reactor will be operated until the overall Reactor Potential decreases to a given fraction of the reaction potential with all new catalyst. This is typically 60 to 70% of the new Reactor Potential. This actual value depends on how the system supplier designed the system in terms of the amount and type of catalyst, and the guaranteed operating hours required by the SCR owner. When this target Reactor Potential is reached additional catalyst must be added, or a layer replaced to increase the overall Reactor Potential, otherwise the target $NO_x$ reduction cannot be achieved while maintaining low ammonia slip.

Using rates of deactivation as determined by laboratory measurements, or using the *in situ* measurements, CatReact™ calculates operating hours and dates at which these catalyst events will need to take place.

CatReact™ is set up as a series of twenty events as shown in Figure 6-1. The events are represented by rows, and the different catalyst layers (up to 5) by columns (Figure 6-1). At each event catalyst can be added, replaced, or removed from each layer. An overall catalyst management scenario is defined by putting an integer, (an integer signifies a specific type of catalyst) at an event and layer where an addition or replacement is to take place. For instance, the case shown in Figure 6-1 is a 3 + 1 layer configuration like Gorgas Unit 10 (3 filled catalyst layers and 1 spare layer). At start up, Layers 1, 2, and 3 are filled with catalyst Type 1 and Layer 4 is empty. At the first event, catalyst Type 1 will be added to Layer 4. At Event 2 Layer 1 will be replaced with new catalyst Type 1; at Event 3 Layer 2 will be replaced, and so forth.

| *Calculation Scenario* | | | | | |
|---|---|---|---|---|---|
| | *Layer 1* | *Layer 2* | *Layer 3* | *Layer 4* | *Layer 5* |
| *Startup* | 1 | 1 | 1 | | |
| *Event 1* | | | | 1 | |
| *Event 2* | 1 | | | | |
| *Event 3* | | 1 | | | |
| *Event 4* | | | 1 | | |
| *Event 5* | | | | 1 | |
| *Event 6* | 1 | | | | |
| *Event 7* | | 1 | | | |
| *Event 8* | | | 1 | | |
| *Event 9* | | | | 1 | |
| *Event 10* | 1 | | | | |
| *Event 11* | | 1 | | | |
| *Event 12* | | | 1 | | |
| *Event 13* | | | | 1 | |
| *Event 14* | 1 | | | | |
| *Event 15* | | 1 | | | |
| *Event 16* | | | 1 | | |
| *Event 17* | 1 | | | | |
| *Event 18* | | 1 | | | |
| *Event 19* | | | 1 | | |
| *Event 20* | | | | 1 | |

*Note: Numbers signify Catalyst Type*

**Figure 6-1. CatReact™ Catalyst Event Structure**

Once the catalyst management scenario is structured, CatReact™ will calculate the operating hours and calendar dates at which these events need to take place. The costs associated with each of these events are also calculated. The way CatReact™ is structured the "events" are in essence the independent parameters and "time" becomes the dependent parameter.

To minimize catalyst cost, one would add or change the catalyst when the Reactor Potential reaches the critical value. While this may minimize catalyst cost, it may not minimize overall operating cost when the costs associated with taking a special outage to change catalyst are factored into the overall operation and maintenance costs. Thus, lower overall costs may be realized by either a) changing the catalyst early during a planned outage, or b) operating at a lower than ideal Reactor Potential until a planned outage is reached. By changing early, catalyst cost will be higher because active catalyst is being discarded. By changing late, either the level of $NO_x$ reduction will need to be decreased to maintain acceptable levels of $NH_3$ slip, or a higher level of $NH_3$ slip will need to be tolerated. Reducing $NO_x$ reduction may compromise meeting a $NO_x$ tonnage cap, or require $NO_x$ credits to be purchased.

The way CatReact™ coordinates with planned outages is shown in Figure 6-2. The user defines two time periods:

1. How many days before an ideal catalyst change event will the catalyst be allowed to be changed (i.e., change early)? The “ideal catalyst change” is when the minimum catalyst potential of the reactor is reached.

2. How many days after an ideal catalyst change event will the user be willing to operate with a lower Reactor Potential than the recommended minimum (i.e., change late)?

3. For a late change, the user then specifies either 1) to maintain $NO_x$ reduction and allow the $NH_3$ slip to increase, or 2) to reduce the $NO_x$ reduction in order not to exceed the maximum $NH_3$ slip.

| | |
|---|---|
| Search Nearest Outage - Days After | 60 |
| Search Nearest Outage - Days Before | 200 |

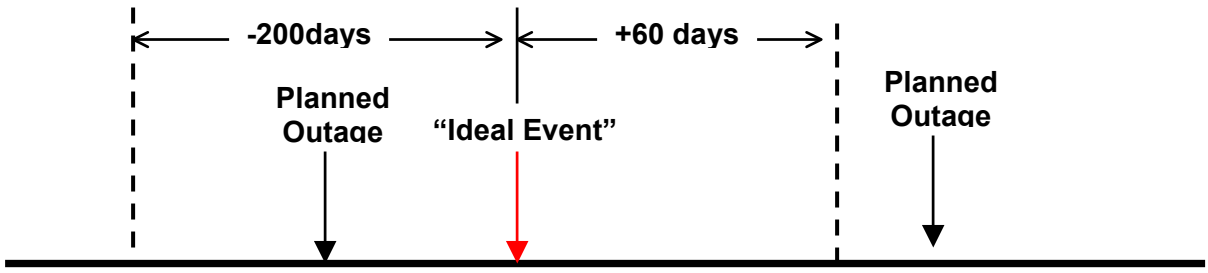



**Figure 6-2. How CatReact™ Considers Planned Outages**

If a planned outage falls within this window as shown in Figure 6-2, then CatReact™ will specify the planned outage instead of the "ideal" outage. If no planned outage falls in this window, the time for the ideal event is specified.

In addition to calculating the time at which each event takes place, the program also calculates the $NO_x$ reduction or $NH_3$ slip just before a catalyst event and just after a catalyst event. For the case where the user elects to allow the catalyst to be changed later than ideal, the program calculates either 1) a reduced $NO_x$ reduction that produces the maximum allowable $NH_3$ slip or 2) how much the $NH_3$ slip will increase if the specified $NO_x$ reduction is maintained. The program then calculates the tons of $NO_x$ that result from reducing the level of $NO_x$ reduction, as well as the cost to purchase the equivalent amount of $NO_x$ credits.

Once all of the times are calculated, the costs associated with a catalyst event are calculated. Upon completion of all of the calculations, the outputs are summarized in both tabular and graphical form.

CatReact™ is an Excel workbook consisting of eleven worksheets (Table 6-1). Due to confidentiality agreements, specific data for the Gorgas 10 SCR cannot be shown. However, CatReact™ was set up with all relevant Gorgas 10 data.

**Table 6-1. CatReact™ Worksheets**

| Worksheet | Function |
|---|---|
| Input Buttons | Buttons to access sheets below, catalyst management scenario |
| Unit Data | Unit size, coal type, etc. |
| SCR Data | SCR process design and operating data |
| Catalyst Data | Specific catalyst data, up to 10 different catalysts |
| Time Factors | Start time, year when annual operation begins, date for the summary report |
| Economic Factors | Discount rate, cost of electricity, etc. |
| Planned Outages | List of planned outage dates and durations |
| Capacity Factors | Capacity factors by year |
| Deactivation | Catalyst layer deactivation rates |
| Output Data | Output from the calculations |
| Blank Sheet | User can paste results from multiple model runs |

For this current project the most relevant worksheet in CatReact™ is the “Deactivation” worksheet. The deactivation worksheet is used to specify the rate at which the catalyst layers deactivate. See Figure 6-3. Four options are available to the user.

1, 2: *Default High and Low Arsenic*
These are two default deactivation rates built into the program representing low and high arsenic flue gas. As a general rule, if the coal arsenic content is less than 15 ppm, the "Default Low Arsenic" deactivation rates may be the most appropriate. If greater than 15 ppm, the "Default High Arsenic" deactivation rates may be more appropriate.

3: *Fit Vendor EOL Estimate*
Instead of using the default deactivation rates, the user may choose to have the program modify the low arsenic deactivation rates to make the first event correspond to the value of the "Vendor Est. Hrs. for 1st Addition" input in the "SCR Data" worksheet.

4: *User Supplied*
The users can specify their own deactivation rates. This can be 1) estimated deactivation rates provided by the vendor, or 2) actual deactivation rates measured from catalyst samples taken from the reactor. This is input in tabular form in terms of $K/K_o$ vs. operating time as shown in Figure 6-3. The top graph on the deactivation worksheet shows the deactivation curves selected by the user. The bottom graph shows the curve fits to the user supplied data.

In the examples that follow, the *in situ* activity measurements will be input in the "user supplied" portion of the spreadsheet, using the *in situ* data.

To illustrate how the *in situ* deactivation measurements are used in catalyst management CatReact™ will be used to explore two case studies:

Case Study No. 1
The Gorgas Unit 10 SCR was designed as a 3+1 system (i.e., three initial catalyst layers with a spare layer filled after deactivation). In this case the initial catalyst is honeycomb. Due to ash deposition, primarily on the first layer, two alternate catalyst management scenarios will be investigated. The first will be to operate the system with only three catalyst layers (i.e., 3+0 design) in order to minimize pressure drop across the SCR.if ID fan capacity is an issue. The second option will be to replace the honeycomb in the first layer with plate catalyst. Note that both of these options result in less Reactor Potential being installed in the reactors. In the case of operating as a 3+0 system, the Reactor Potential of an entire layer is not used. In the case of the plate catalyst, which as a lower specific surface area, the Reactor Potential of the top layer is reduced by nominally 15%.

CatReact™ will be used to determine the addition and replacement times as well as overall costs.

Case Study No. 2
In the first case study, a nominal time window for changing the catalyst before and after reaching "end of life" will be defined (see Figure 6-2). With this approach not all of the catalyst events will likely take place during planned outages, thus special outages will need to be taken to add or replace catalyst layers.

In this second case study the time window for changing catalyst will be enlarged, either for early changes before "end of life" is reached, or later changes operating at reduced $NO_x$ reduction levels to maintain $NH_3$ slip in order to avoid any special outages.

Table 6-2 shows the deactivation data that was input to CatReact™. To illustrate this on a consistent basis the 2005 ozone season *in situ* data and the first measurements in the 2006 ozone season were used as the basis for the calculations. Due to the malfunctioning sootblowers, the remainder of the 2006 *in situ* data was deemed to be not representative. By including the first measurements made in the 2006 ozone season the increase in Reactor Potential for Layers 2 and 3 due to vacuuming is taken into account. Figure 6-4 shows the layer-by-layer deactivation curves.

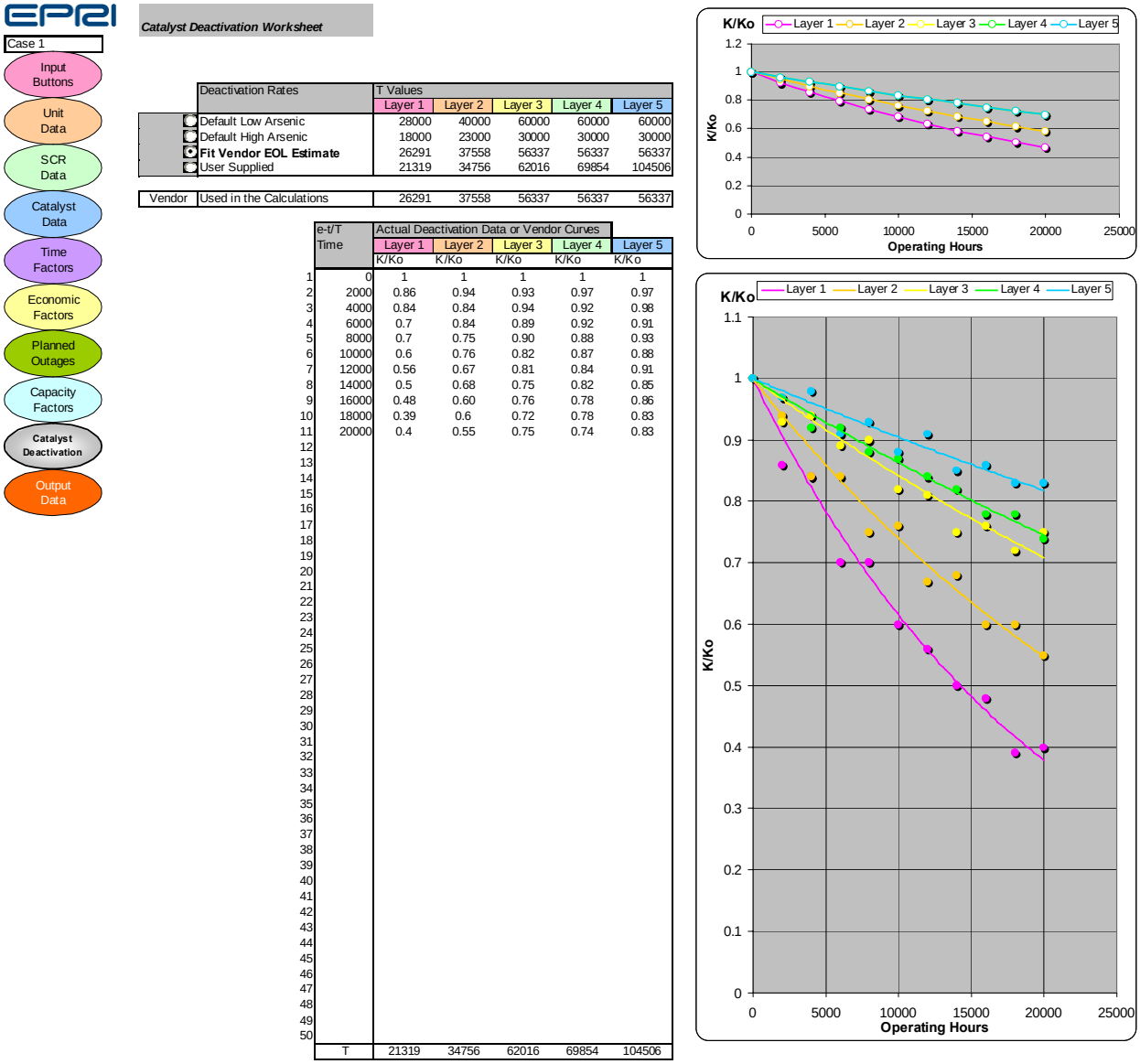



**Figure 6-3. CatReact™ Deactivation Worksheet**

**Table 6-2. Deactivation Data Used in CatReact™**

| | RP/RPo | | |
|---|---|---|---|
| t, hrs | Layer 1 | Layer 2 | Layer 3 |
| 0 | 1 | 1 | 1 |
| 11570 | 0.6 | 0.68 | 0.76 |
| 12266 | 0.51 | 0.66 | 0.80 |
| 13070 | 0.49 | 0.62 | 0.74 |
| 13766 | 0.485 | 0.60 | 0.79 |
| 14270 | 0.47 | 0.57 | 0.72 |
| 15098 | | 0.63 | 0.77 |

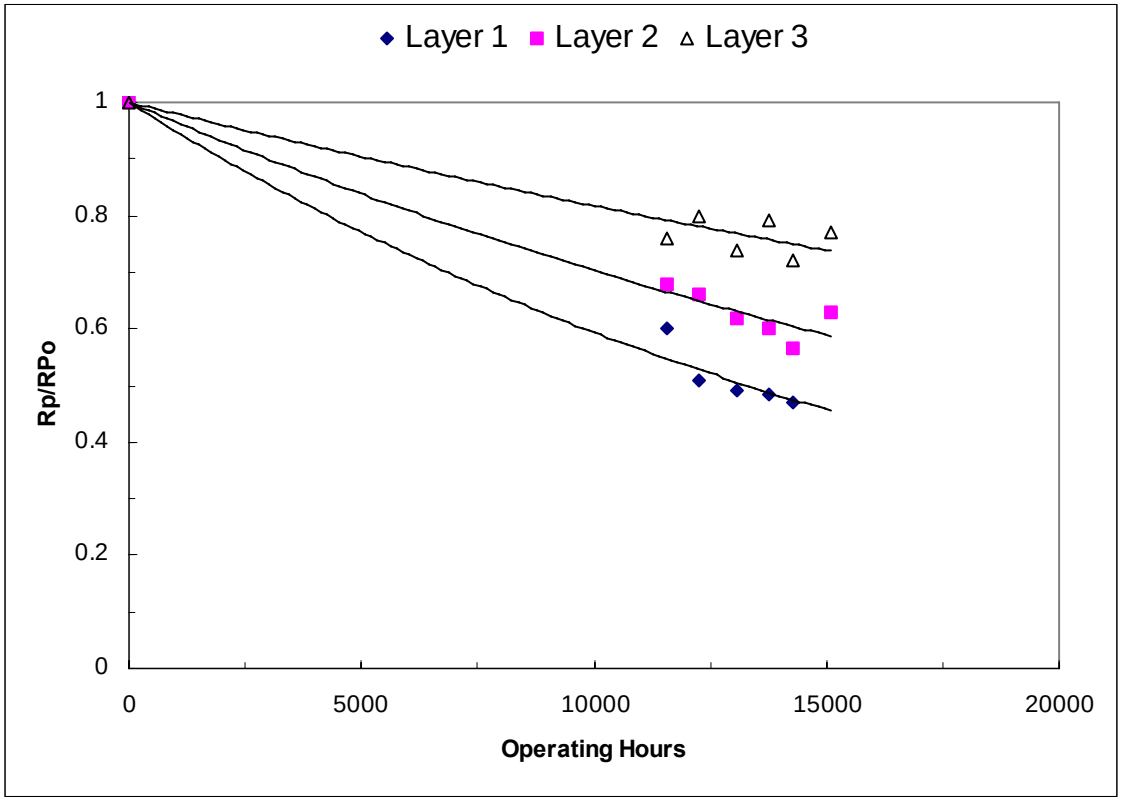



**Figure 6-4. Exponential Curve Fits Used by CatReact™**

In addition to the deactivation data, the following assumptions were also made:

- The SCR started May 2002.
- The SCR will switch from ozone seasonal operation to year round operation in 2009.
- Catalyst Layer 4 deactivation rates are the same as Layer 3.
- Unit outages (30 days each) are scheduled every two years in February (note these are not Gorgas's actual planned outages but are for illustration only).
- For Case Study No. 1 Gorgas is willing to change the catalyst 120 days early or 90 days after "end of life" is reached in order to coordinate a catalyst addition outage. In the event that the catalyst is changed after end of life, $NO_x$ reduction will be reduced to maintain $NH_3$ slip and $NO_x$ credits will be purchased.
- Other economic factors are included in Table 6-3 (again, these are not the actual Gorgas values and are used for illustration only).

**Table 6-3. CatReact™ Economic Factors**

| Parameter | Units | Value |
|---|---|---|
| Discount Rate | % | 5 |
| $NO_x$ Allowance Cost | $/ton | 2,500 |
| Outage Labor Cost | $/Layer | 100,000 |
| Cost of Electricity | $/MW- hr | 20 |
| Reagent Cost | $/ton | 250 |
| Catalyst Cost (*) | $/m^3 | 6,200 |

(*) Both honeycomb and Plate catalysts

Case Study No. 1 Results

Again, this case study explores three different catalyst management scenarios:

a. Design 3+1 configuration (all honeycomb catalysts)
b. Alternate 3+0 configuration
c. Design 3+1 configuration (plate catalyst used in the first layer)

Figure 6-5 shows how each of these three cases is specified in CatReact™. CatReact™ can define up to ten different catalysts, each is given an integer value from 1 to 10. The catalyst worksheet contains all of the pertinent catalyst data for each catalyst. For the cases discussed in this section, Catalyst "1" is the honeycomb catalyst and catalyst "3" is the plate catalyst used at Gorgas Unit 10.

Case 1a in Figure 6-5 shows the 3+1 catalyst management scenario. In this case the first catalyst event involves filling the fourth layer. Thereafter, catalyst is sequentially changed in Layers 1 – 4; all changes using honeycomb catalyst.

Case 1b in Figure 6-5 shows the 3+0 catalyst management scenario, again using only the honeycomb catalyst.

| | Case 1a | | | | | Case 1b | | | | | Case 1c | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 |
| Start | 1 | 1 | 1 | | | 1 | 1 | 1 | | | 1 | 1 | 1 | | |
| Event 1 | | | | 1 | | 1 | | | | | 3 | | | | |
| Event 2 | 1 | | | | | | 1 | | | | | | | 1 | |
| Event 3 | | 1 | | | | | | 1 | | | | 1 | | | |
| Event 4 | | | 1 | | | 1 | | | | | | | 1 | | |
| Event 5 | | | | 1 | | | 1 | | | | 3 | | | | |
| Event 6 | 1 | | | | | | | 1 | | | | | | 1 | |
| Event 7 | | 1 | | | | 1 | | | | | | 1 | | | |
| Event 8 | | | 1 | | | | 1 | | | | | | 1 | | |
| Event 9 | | | | 1 | | | | 1 | | | 3 | | | | |
| Event 10 | 1 | | | | | 1 | | | | | | | | 1 | |
| Event 11 | | 1 | | | | | 1 | | | | | 1 | | | |
| Event 12 | | | 1 | | | | | 1 | | | | | 1 | | |
| Event 13 | | | | 1 | | 1 | | | | | 3 | | | | |
| Event 14 | 1 | | | | | | 1 | | | | | | | 1 | |
| Event 15 | | 1 | | | | | | 1 | | | | 1 | | | |
| Event 16 | | | 1 | | | 1 | | | | | | | 1 | | |
| Event 17 | | | | 1 | | | 1 | | | | 3 | | | | |
| Event 18 | 1 | | | | | | | 1 | | | | | | 1 | |
| Event 19 | | 1 | | | | 1 | | | | | | 1 | | | |
| Event 20 | | | 1 | | | | 1 | | | | | | 1 | | |

**Figure 6-5. Case Study 1: Various CatReact™ Catalyst Management Scenarios**

Case 1c shows how the catalyst management scenario whereby plate catalyst is replaced into the first layer as the first catalyst event. In this case the second catalyst event entails filling the fourth layer with honeycomb. Thereafter, each layer is replaced sequentially with plate catalyst being used in the first layer.

The latter two configurations are considered in order to reduce pressure drop and deal with ash deposition, primarily on the first layer.

CatReact™ was run for these three cases. The tabular output from CatReact™ for each case is shown in Tables 6-4, 6-5, and 6-6. A summary for the three cases for a 20-year operating period is shown in Table 6-7. Note the costs shown in these tables are net present value costs using the discount rate shown in Table 6-3.

As expected, the least cost approach is the original design basis (3+1) using honeycomb catalyst (Case 1a). The overall twenty-year costs are calculated to be 42.2 million dollars, of which the catalyst cost is 11.6 million dollars. Note, the reagent cost is almost twice the catalyst cost. Also, one can see estimated replacement power costs of nominally 7.3 million dollars, which is associated with having to take special outages to replace catalyst. Also, due to the assumptions made, some of the catalyst replacements occur after "end of life" requiring a reduced $NO_x$ reduction and the purchase of 2.6 million dollars of $NO_x$ credits. With this base scenario there would be ten (10) catalyst events over a twenty-year period.

If the plant chose to operate the SCR system in a 3+0 configuration (Case 1b) the number of catalyst events over a twenty-year period would increase from ten (10) to thirteen (13). This is a consequence of having less Reactor Potential in the reactor. Overall costs are increased by 16.7 million dollars to 58.9 million dollars. The increases being primarily catalyst, replacement power, and $NO_x$ credit costs.

Finally, the scenario of using plate catalyst in the first layer (Case 1c) also increases the twenty-year costs by about 6.6 million dollars to 48.8 million. This is a consequence of one more catalyst event being needed (eleven versus ten) over the twenty-year period. Again, this is due to the slightly lower Reactor Potential associated with the layer of plate catalyst.

Based on three CatReact™ calculations, operating the Gorgas Unit 10 SCR as a 3+0 configuration would not likely be a recommended approach. Operating with the plate catalyst in Layer 1 may increase operating costs somewhat but will likely be beneficial overall from an ash deposition point of view.

Case Study No. 2 Results

From Table 6-7 (Case 1c), using the plate catalyst in the first layer, eleven catalyst events were required over a twenty-year period. Based on the assumption made in terms of changing early (120 days) or late (90 days) relative to "end-of-life" only three occurred coincident with planned outages; eight required special outages.

In this second case study, the time windows are widened to make the catalyst events coincide with planned outages. To do this, the following time windows were explored:

- Change up to 650 days early
- Change up to 550 days after end-of-life
- Change up to 365 days early or late

## Table 6-4. Case Study 1 (1a): Design Base 3+1 Configuration

| Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | | Date | Operating Hours | Total Cost | dNOx | NH3slip | Cost Components | | | | | | SO2 Conv | dP | RP/RPo ( used) | RP/RPo (new) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | hrs | $10^6 | % | ppm | Catalyst $10^6 | Reagent $10^6 | Labor $10^6 | Electricity $10^6 | NOx Credit $10^6 | dP $10^6 | % | in H2O | | |
| 1 | 1 | 1 | | | Start | 5/1/2002 | 0 | $ - | 85 | 0.1 | $ - | $ - | $ - | $ - | $ - | $ - | 0.5% | 1.3 | | 1.00 |
| | | | 1 | | Event 1 | 2/1/2006 | 14,688 | $ 5.63 | 85 | 1.91 | $ 1.76 | $ 3.65 | $ 0.08 | $ - | $ - | $ 0.14 | 0.7% | 1.7 | 0.60 | 0.94 |
| 1 | | | | | Event 2 | 2/1/2010 | 34,464 | $ 11.45 | 58 | 2.00 | $ 3.21 | $ 7.01 | $ 0.15 | $ - | $ 0.73 | $ 0.35 | 0.7% | 1.7 | 0.55 | 0.83 |
| | 1 | | | | Event 3 | 7/3/2011 | 46,157 | $ 16.51 | 64 | 2.00 | $ 4.56 | $ 8.75 | $ 0.22 | $ 1.50 | $ 1.04 | $ 0.45 | 0.7% | 1.7 | 0.56 | 0.83 |
| | | 1 | | | Event 4 | 12/27/2012 | 58,240 | $ 21.26 | 64 | 2.00 | $ 5.82 | $ 10.41 | $ 0.28 | $ 2.90 | $ 1.32 | $ 0.53 | 0.7% | 1.7 | 0.56 | 0.79 |
| | | | 1 | | Event 5 | 6/25/2014 | 70,351 | $ 25.64 | 67 | 2.00 | $ 6.98 | $ 11.97 | $ 0.33 | $ 4.20 | $ 1.54 | $ 0.61 | 0.7% | 1.7 | 0.57 | 0.79 |
| 1 | | | | | Event 6 | 2/1/2016 | 84,168 | $ 28.73 | 67 | 2.00 | $ 8.06 | $ 13.60 | $ 0.38 | $ 4.20 | $ 1.79 | $ 0.70 | 0.7% | 1.7 | 0.57 | 0.88 |
| | 1 | | | | Event 7 | 9/27/2017 | 97,949 | $ 32.69 | 65 | 2.00 | $ 9.06 | $ 15.11 | $ 0.43 | $ 5.31 | $ 2.00 | $ 0.78 | 0.7% | 1.7 | 0.56 | 0.84 |
| | | 1 | | | Event 8 | 4/28/2019 | 110,865 | $ 36.26 | 65 | 2.00 | $ 9.98 | $ 16.42 | $ 0.47 | $ 6.33 | $ 2.21 | $ 0.84 | 0.7% | 1.7 | 0.56 | 0.78 |
| | | | 1 | | Event 9 | 10/9/2020 | 122,640 | $ 39.44 | 68 | 2.00 | $ 10.84 | $ 17.53 | $ 0.51 | $ 7.29 | $ 2.37 | $ 0.90 | 0.7% | 1.7 | 0.57 | 0.78 |
| 1 | | | | | Event 10 | 2/1/2022 | 133,176 | $ 41.27 | 85 | 1.83 | $ 11.65 | $ 18.46 | $ 0.55 | $ 7.29 | $ 2.37 | $ 0.95 | 0.7% | 1.7 | 0.61 | 0.92 |
| | 1 | | | | Event 11 | 2/1/2024 | 150,696 | $ 44.06 | 50 | 2.00 | $ 12.38 | $ 19.87 | $ 0.59 | $ 7.29 | $ 2.92 | $ 1.02 | 0.7% | 1.7 | 0.53 | 0.81 |
| | | 1 | | | Event 12 | 7/10/2025 | 162,599 | $ 46.61 | 65 | 2.00 | $ 13.06 | $ 20.76 | $ 0.62 | $ 8.05 | $ 3.06 | $ 1.07 | 0.7% | 1.7 | 0.56 | 0.78 |
| | | | 1 | | Event 13 | 12/24/2026 | 174,391 | $ 48.97 | 68 | 2.00 | $ 13.69 | $ 21.58 | $ 0.65 | $ 8.75 | $ 3.18 | $ 1.11 | 0.7% | 1.7 | 0.57 | 0.78 |
| 1 | | | | | Event 14 | 8/5/2028 | 187,605 | $ 51.22 | 70 | 2.00 | $ 14.28 | $ 22.43 | $ 0.68 | $ 9.41 | $ 3.28 | $ 1.16 | 0.7% | 1.7 | 0.57 | 0.89 |
| | 1 | | | | Event 15 | 2/1/2030 | 199,704 | $ 52.56 | 85 | 1.96 | $ 14.83 | $ 23.15 | $ 0.70 | $ 9.41 | $ 3.28 | $ 1.19 | 0.7% | 1.7 | 0.60 | 0.87 |
| | | 1 | | | Event 16 | 9/11/2031 | 213,806 | $ 54.58 | 65 | 2.00 | $ 15.33 | $ 23.93 | $ 0.73 | $ 9.97 | $ 3.39 | $ 1.23 | 0.7% | 1.7 | 0.56 | 0.77 |
| | | | 1 | | Event 17 | 2/17/2033 | 225,443 | $ 56.31 | 68 | 2.00 | $ 15.80 | $ 24.53 | $ 0.75 | $ 10.49 | $ 3.48 | $ 1.26 | 0.7% | 1.7 | 0.57 | 0.78 |
| 1 | | | | | Event 18 | 9/24/2034 | 238,511 | $ 57.98 | 70 | 2.00 | $ 16.23 | $ 25.16 | $ 0.77 | $ 10.97 | $ 3.55 | $ 1.30 | 0.7% | 1.7 | 0.57 | 0.88 |
| | 1 | | | | Event 19 | 6/11/2036 | 252,574 | $ 59.58 | 65 | 2.00 | $ 16.63 | $ 25.77 | $ 0.79 | $ 11.42 | $ 3.64 | $ 1.33 | 0.7% | 1.7 | 0.56 | 0.84 |
| | | 1 | | | Event 20 | 2/1/2038 | 266,712 | $ 60.74 | 56 | 2.00 | $ 17.00 | $ 26.35 | $ 0.80 | $ 11.42 | $ 3.81 | $ 1.36 | 0.7% | 1.7 | 0.54 | 0.76 |

Note: In the above output tables "black" entry dates correspond to planned outages
"red" entry dates correspond to special outages just to add or replace catalyst

## Table 6-5. Case Study 1 (1b): 3+0 Configuration

| Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | | Date | Operating Hours | Total Cost | dNOx | NH3slip | Cost Components | | | | | | SO2 Conv | dP | RP/RPo ( used) | RP/RPo (new) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | hrs | $10^6 | % | ppm | Catalyst $10^6 | Reagent $10^6 | Labor $10^6 | Electricity $10^6 | NOx Credit $10^6 | dP $10^6 | % | in H2O | | |
| 1 | 1 | 1 | | | Start | 5/1/2002 | 0 | $ - | 85 | 0.1 | $ - | $ - | $ - | $ - | $ - | $ - | 0.5% | 1.3 | | 1.00 |
| 1 | | | | | Event 1 | 2/1/2006 | 14,688 | $ 5.63 | 85 | 1.91 | $ 1.76 | $ 3.65 | $ 0.08 | $ - | $ - | $ 0.14 | 0.5% | 1.3 | 0.60 | 0.78 |
| | 1 | | | | Event 2 | 2/1/2008 | 24,168 | $ 10.05 | 60 | 2.00 | $ 3.36 | $ 5.71 | $ 0.16 | $ - | $ 0.59 | $ 0.22 | 0.5% | 1.3 | 0.55 | 0.74 |
| | | 1 | | | Event 3 | 2/1/2010 | 36,624 | $ 16.34 | 34 | 2.00 | $ 4.80 | $ 7.83 | $ 0.23 | $ - | $ 3.15 | $ 0.32 | 0.5% | 1.3 | 0.48 | 0.65 |
| 1 | | | | | Event 4 | 12/24/2010 | 43,734 | $ 21.78 | 50 | 2.00 | $ 6.19 | $ 8.99 | $ 0.29 | $ 1.65 | $ 4.29 | $ 0.36 | 0.5% | 1.3 | 0.53 | 0.79 |
| | 1 | | | | Event 5 | 6/13/2012 | 55,664 | $ 27.45 | 45 | 2.00 | $ 7.48 | $ 10.68 | $ 0.35 | $ 3.09 | $ 5.41 | $ 0.44 | 0.5% | 1.3 | 0.52 | 0.74 |
| | | 1 | | | Event 6 | 9/1/2013 | 66,108 | $ 32.55 | 46 | 2.00 | $ 8.70 | $ 12.07 | $ 0.41 | $ 4.44 | $ 6.44 | $ 0.49 | 0.5% | 1.3 | 0.52 | 0.67 |
| 1 | | | | | Event 7 | 9/1/2014 | 73,899 | $ 36.96 | 50 | 2.00 | $ 9.85 | $ 13.06 | $ 0.47 | $ 5.73 | $ 7.32 | $ 0.53 | 0.5% | 1.3 | 0.53 | 0.79 |
| | 1 | | | | Event 8 | 2/1/2016 | 86,088 | $ 40.58 | 44 | 2.00 | $ 10.93 | $ 14.51 | $ 0.52 | $ 5.73 | $ 8.31 | $ 0.58 | 0.5% | 1.3 | 0.51 | 0.73 |
| | | 1 | | | Event 9 | 4/29/2017 | 96,262 | $ 44.81 | 46 | 2.00 | $ 11.95 | $ 15.64 | $ 0.57 | $ 6.86 | $ 9.17 | $ 0.63 | 0.5% | 1.3 | 0.52 | 0.67 |
| 1 | | | | | Event 10 | 2/1/2018 | 101,952 | $ 46.67 | 66 | 2.00 | $ 12.93 | $ 16.25 | $ 0.61 | $ 6.86 | $ 9.37 | $ 0.65 | 0.5% | 1.3 | 0.56 | 0.82 |
| | 1 | | | | Event 11 | 7/31/2019 | 115,043 | $ 50.78 | 46 | 2.00 | $ 13.84 | $ 17.56 | $ 0.65 | $ 7.87 | $ 10.15 | $ 0.70 | 0.5% | 1.3 | 0.52 | 0.73 |
| | | 1 | | | Event 12 | 11/3/2020 | 125,157 | $ 54.34 | 47 | 2.00 | $ 14.70 | $ 18.51 | $ 0.70 | $ 8.82 | $ 10.87 | $ 0.74 | 0.5% | 1.3 | 0.52 | 0.66 |
| 1 | | | | | Event 13 | 10/1/2021 | 132,876 | $ 57.46 | 50 | 2.00 | $ 15.52 | $ 19.21 | $ 0.73 | $ 9.74 | $ 11.50 | $ 0.77 | 0.5% | 1.3 | 0.53 | 0.80 |
| | 1 | | | | Event 14 | 4/1/2023 | 145,045 | $ 60.82 | 45 | 2.00 | $ 16.28 | $ 20.22 | $ 0.77 | $ 10.58 | $ 12.16 | $ 0.81 | 0.5% | 1.3 | 0.52 | 0.73 |
| | | 1 | | | Event 15 | 7/9/2024 | 155,244 | $ 63.80 | 46 | 2.00 | $ 16.99 | $ 21.03 | $ 0.80 | $ 11.38 | $ 12.76 | $ 0.84 | 0.5% | 1.3 | 0.52 | 0.67 |
| 1 | | | | | Event 16 | 6/13/2025 | 163,136 | $ 66.42 | 50 | 2.00 | $ 17.68 | $ 21.62 | $ 0.84 | $ 12.14 | $ 13.29 | $ 0.86 | 0.5% | 1.3 | 0.53 | 0.79 |
| | 1 | | | | Event 17 | 12/8/2026 | 175,208 | $ 69.22 | 45 | 2.00 | $ 18.31 | $ 22.46 | $ 0.87 | $ 12.85 | $ 13.84 | $ 0.89 | 0.5% | 1.3 | 0.52 | 0.73 |
| | | 1 | | | Event 18 | 2/1/2028 | 184,320 | $ 70.78 | 54 | 2.00 | $ 18.91 | $ 23.06 | $ 0.89 | $ 12.85 | $ 14.14 | $ 0.92 | 0.5% | 1.3 | 0.54 | 0.68 |
| 1 | | | | | Event 19 | 1/25/2029 | 192,955 | $ 73.02 | 50 | 2.00 | $ 19.49 | $ 23.60 | $ 0.92 | $ 13.48 | $ 14.58 | $ 0.94 | 0.5% | 1.3 | 0.53 | 0.79 |
| | 1 | | | | Event 20 | 7/19/2030 | 204,937 | $ 75.36 | 45 | 2.00 | $ 20.02 | $ 24.31 | $ 0.95 | $ 14.08 | $ 15.05 | $ 0.96 | 0.5% | 1.3 | 0.52 | 0.73 |

Note: In the above output tables "black" entry dates correspond to planned outages
"red" entry dates correspond to special outages just to add or replace catalyst

## Table 6-6. Case Study 1 (1c): 3 + 1 Configuration, Plate Catalyst in Layer 1

| Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | | Date | Operating Hours | Total Cost | dNOx | NH3slip | Cost Components | | | | | | SO2 Conv | dP | RP/RPo ( used) | RP/RPo (new) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | hrs | $10^6 | % | ppm | Catalyst $10^6 | Reagent $10^6 | Labor $10^6 | Electricity $10^6 | NOx Credit $10^6 | dP $10^6 | % | in H2O | | |
| 1 | 1 | 1 | | | Start | 5/1/2002 | 0 | $ - | 85 | 0.1 | $ - | $ - | $ - | $ - | $ - | $ - | 0.5% | 1.3 | | 1.00 |
| 3 | | | | | Event 1 | 2/1/2006 | 14,688 | $ 6.00 | 85 | 1.91 | $ 2.13 | $ 3.65 | $ 0.08 | $ - | $ - | $ 0.14 | 0.5% | 1.2 | 0.60 | 0.72 |
| | | | 1 | | Event 2 | 6/30/2007 | 21,943 | $ 12.24 | 62 | 2.00 | $ 3.77 | $ 5.29 | $ 0.16 | $ 2.30 | $ 0.51 | $ 0.20 | 0.7% | 1.7 | 0.56 | 0.89 |
| | 1 | | | | Event 3 | 8/12/2010 | 38,123 | $ 18.53 | 67 | 2.00 | $ 5.18 | $ 7.98 | $ 0.23 | $ 3.98 | $ 0.80 | $ 0.36 | 0.7% | 1.7 | 0.57 | 0.81 |
| | | 1 | | | Event 4 | 2/1/2012 | 50,064 | $ 21.82 | 74 | 2.00 | $ 6.49 | $ 9.70 | $ 0.29 | $ 3.98 | $ 0.91 | $ 0.46 | 0.7% | 1.7 | 0.58 | 0.79 |
| 3 | | | | | Event 5 | 7/19/2013 | 62,896 | $ 26.74 | 69 | 2.00 | $ 7.97 | $ 11.42 | $ 0.35 | $ 5.34 | $ 1.12 | $ 0.54 | 0.7% | 1.7 | 0.57 | 0.82 |
| | | | 1 | | Event 6 | 1/4/2015 | 74,738 | $ 31.01 | 65 | 2.00 | $ 9.11 | $ 12.90 | $ 0.40 | $ 6.61 | $ 1.38 | $ 0.62 | 0.7% | 1.7 | 0.56 | 0.78 |
| | 1 | | | | Event 7 | 6/15/2016 | 86,449 | $ 34.93 | 68 | 2.00 | $ 10.17 | $ 14.26 | $ 0.45 | $ 7.79 | $ 1.57 | $ 0.68 | 0.7% | 1.7 | 0.57 | 0.84 |
| | | 1 | | | Event 8 | 2/1/2018 | 100,512 | $ 37.74 | 67 | 2.00 | $ 11.15 | $ 15.77 | $ 0.50 | $ 7.79 | $ 1.77 | $ 0.76 | 0.7% | 1.7 | 0.57 | 0.77 |
| 3 | | | | | Event 9 | 8/2/2019 | 112,922 | $ 41.36 | 69 | 2.00 | $ 12.25 | $ 17.01 | $ 0.54 | $ 8.80 | $ 1.93 | $ 0.82 | 0.7% | 1.7 | 0.57 | 0.82 |
| | | | 1 | | Event 10 | 1/23/2021 | 124,921 | $ 44.55 | 65 | 2.00 | $ 13.10 | $ 18.13 | $ 0.58 | $ 9.74 | $ 2.12 | $ 0.88 | 0.7% | 1.7 | 0.56 | 0.77 |
| | 1 | | | | Event 11 | 6/24/2022 | 136,377 | $ 47.44 | 68 | 2.00 | $ 13.89 | $ 19.12 | $ 0.62 | $ 10.62 | $ 2.26 | $ 0.93 | 0.7% | 1.7 | 0.57 | 0.84 |
| | | 1 | | | Event 12 | 2/1/2024 | 149,496 | $ 49.35 | 77 | 2.00 | $ 14.62 | $ 20.18 | $ 0.65 | $ 10.62 | $ 2.30 | $ 0.98 | 0.7% | 1.7 | 0.58 | 0.79 |
| 3 | | | | | Event 13 | 7/29/2025 | 162,574 | $ 52.10 | 69 | 2.00 | $ 15.44 | $ 21.15 | $ 0.69 | $ 11.38 | $ 2.42 | $ 1.03 | 0.7% | 1.7 | 0.57 | 0.82 |
| | | | 1 | | Event 14 | 1/19/2027 | 174,544 | $ 54.48 | 65 | 2.00 | $ 16.07 | $ 21.98 | $ 0.72 | $ 12.08 | $ 2.55 | $ 1.07 | 0.7% | 1.7 | 0.56 | 0.77 |
| | 1 | | | | Event 15 | 6/16/2028 | 185,914 | $ 56.64 | 68 | 2.00 | $ 16.66 | $ 22.72 | $ 0.74 | $ 12.74 | $ 2.66 | $ 1.11 | 0.7% | 1.7 | 0.57 | 0.84 |
| | | 1 | | | Event 16 | 2/1/2030 | 199,224 | $ 58.08 | 74 | 2.00 | $ 17.21 | $ 23.52 | $ 0.77 | $ 12.74 | $ 2.70 | $ 1.15 | 0.7% | 1.7 | 0.58 | 0.79 |
| 3 | | | | | Event 17 | 7/26/2031 | 212,207 | $ 60.13 | 69 | 2.00 | $ 17.82 | $ 24.24 | $ 0.79 | $ 13.30 | $ 2.79 | $ 1.19 | 0.7% | 1.7 | 0.57 | 0.82 |
| | | | 1 | | Event 18 | 1/15/2033 | 224,180 | $ 61.91 | 65 | 2.00 | $ 18.29 | $ 24.86 | $ 0.82 | $ 13.83 | $ 2.90 | $ 1.22 | 0.7% | 1.7 | 0.56 | 0.77 |
| | 1 | | | | Event 19 | 6/13/2034 | 235,555 | $ 63.52 | 68 | 2.00 | $ 18.73 | $ 25.41 | $ 0.84 | $ 14.32 | $ 2.98 | $ 1.24 | 0.7% | 1.7 | 0.57 | 0.84 |
| | | 1 | | | Event 20 | 2/1/2036 | 248,928 | $ 64.60 | 74 | 2.00 | $ 19.14 | $ 26.01 | $ 0.86 | $ 14.32 | $ 3.01 | $ 1.28 | 0.7% | 1.7 | 0.58 | 0.79 |

Note: In the above output tables "black" entry dates correspond to planned outages
"red" entry dates correspond to special outages just to add or replace catalyst

## Table 6-7. Twenty Year Summary Case Study No. 1

| | Case 1a | | | | | Case 1b | | | | | Case 1c | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 |
| Start | 1 | 1 | 1 | | | 1 | 1 | 1 | | | 1 | 1 | 1 | | |
| Event 1 | | | | 1 | | 1 | | | | | 3 | | | | |
| Event 2 | 1 | | | | | | 1 | | | | | | | 1 | |
| Event 3 | | 1 | | | | | | 1 | | | | 1 | | | |
| Event 4 | | | 1 | | | 1 | | | | | | | 1 | | |
| Event 5 | | | | 1 | | | 1 | | | | 3 | | | | |
| Event 6 | 1 | | | | | | | 1 | | | | | | 1 | |
| Event 7 | | 1 | | | | 1 | | | | | | 1 | | | |
| Event 8 | | | 1 | | | | 1 | | | | | | 1 | | |
| Event 9 | | | | 1 | | | | 1 | | | 3 | | | | |
| Event 10 | 1 | | | | | 1 | | | | | | | | 1 | |
| Event 11 | | 1 | | | | | 1 | | | | | 1 | | | |
| Event 12 | | | 1 | | | | | 1 | | | | | 1 | | |
| Event 13 | | | | 1 | | 1 | | | | | 3 | | | | |
| Event 14 | 1 | | | | | | 1 | | | | | | | 1 | |
| Event 15 | | 1 | | | | | | 1 | | | | 1 | | | |
| Event 16 | | | 1 | | | 1 | | | | | | | 1 | | |
| Event 17 | | | | 1 | | | 1 | | | | 3 | | | | |
| Event 18 | 1 | | | | | | | 1 | | | | | | 1 | |
| Event 19 | | 1 | | | | 1 | | | | | | 1 | | | |
| Event 20 | | | 1 | | | | 1 | | | | | | 1 | | |

| **Summary Report** | **3+1** | **3+0** | **3+1Plate** |
|---|---|---|---|
| As of Date | **12/31/22** | **12/31/22** | **12/31/22** |
| Total Cost NPV | **$ 45,137,569** | **$ 63,359,330** | **$ 49,755,460** |
| Catalyst NPV | $ 13,068,692 | $ 16,667,577 | $ 15,302,859 |
| Reagent NPV | $ 19,070,008 | $ 19,942,226 | $ 19,581,103 |
| Labor NPV | $ 618,139 | $ 788,363 | $ 684,325 |
| Electricity NPV | $ 9,040,281 | $ 10,249,495 | $ 9,757,481 |
| NOx Credit NPV | $ 2,365,086 | $ 14,920,096 | $ 3,476,486 |
| dP NPV | $ 975,363 | $ 791,573 | $ 953,206 |
| Catalyst Layers Install | 11 | 14 | 12 |

The tabular results for these cases are shown in Tables 6-8, 6-9, 6-10, and summarized for a twenty-year period in Table 6-11. For the case of changing the catalyst early, before end of life is reached, Table 6-8 shows that basically every other outage two layers of catalyst need to be changed at the same time. Also, as can be seen in Table 6-8, even replacing two layers at a time for catalyst events 5 and 6, the Reactor Potential dropped below the minimum required. This required the $NO_x$ reduction to be reduced from 85% to 78% along with the purchase of $NO_x$ credits.

For the case of changing late (i.e., after end of life), Table 6-9, a catalyst layer is replaced at every two years. However, this case is of little practical use since as shown in Table 6-9, the $NO_x$ reduction must be reduced from 85% to nominally 25 – 30% to maintain 2 ppm $NH_3$ slip. In essence, the SCR is not being used and $NO_x$ credits are being purchased.

For the final case where the change out window was set at plus or minus 365 days relative to end of life, Table 6-10, the results selected by CatReact™ were not too different than always changing late; again, not a practical scenario.

Looking at the twenty-year summary in Table 6-11, if all of the catalyst changes are made early to coincide with planned outages, overall costs can potentially be reduced from 48.8 million to 41.1 million dollars, even though catalyst costs increase from 14.3 to 20.2 million dollars. The reduction being the elimination of any replacement power costs and 2.2 million dollars of $NO_x$ credit costs for the base case.

The above two case studies illustrate how complex catalyst management decisions can be. If the forecasting is to be accurate, reliable and accurate deactivation data is pivotal.

## Table 6-8. Case Study 2 (2a): 3+1 Configuration, Plate Catalyst in Layer 1, Change up to 650 Days Early

| Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | | Date | Operating Hours | Total Cost | dNOx | NH3slip | Cost Components | | | | | | SO2 Conv | dP | RP/RPo ( used) | RP/RPo (new) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | hrs | $10^6 | % | ppm | Catalyst $10^6 | Reagent $10^6 | Labor $10^6 | Electricity $10^6 | IOx Credit $10^6 | dP $10^6 | % | in H2O | | |
| 1 | 1 | 1 | | | Start | 5/1/2002 | 0 | $ - | 85 | 0.1 | $ - | $ - | $ - | $ - | $ - | $ - | 0.5% | 1.3 | | 1.00 |
| 3 | | | | | Event 1 | 2/1/2006 | 14,688 | $ 6.00 | 85 | 1.91 | $ 2.13 | $ 3.65 | $ 0.08 | $ - | $ - | $ 0.14 | 0.5% | 1.2 | 0.60 | 0.72 |
| | | | 1 | | Event 2 | 2/1/2006 | 14,688 | $ 7.84 | 85 | 1.91 | $ 3.89 | $ 3.65 | $ 0.17 | $ - | $ - | $ 0.14 | 0.7% | 1.7 | - | 1.05 |
| 3 | | | | | Event 3 | 2/1/2010 | 33,744 | $ 13.10 | 85 | 1.90 | $ 5.64 | $ 6.89 | $ 0.23 | $ - | $ - | $ 0.34 | 0.7% | 1.7 | 0.60 | 0.78 |
| | 1 | | | | Event 4 | 2/1/2010 | 33,744 | $ 14.62 | 85 | 1.90 | $ 7.08 | $ 6.89 | $ 0.30 | $ - | $ - | $ 0.34 | 0.7% | 1.7 | - | 1.01 |
| | | 1 | | | Event 5 | 2/1/2012 | 50,544 | $ 18.58 | 78 | 2.00 | $ 8.40 | $ 9.31 | $ 0.37 | $ - | $ 0.04 | $ 0.47 | 0.7% | 1.7 | 0.59 | 0.79 |
| | | | 1 | | Event 6 | 2/1/2012 | 50,544 | $ 19.95 | 78 | 2.00 | $ 9.71 | $ 9.31 | $ 0.43 | $ - | $ 0.04 | $ 0.47 | 0.7% | 1.7 | - | 0.96 |
| 3 | | | | | Event 7 | 2/1/2014 | 67,368 | $ 23.76 | 85 | 1.57 | $ 11.15 | $ 11.51 | $ 0.48 | $ - | $ 0.04 | $ 0.58 | 0.7% | 1.7 | 0.63 | 0.85 |
| | 1 | | | | Event 8 | 2/1/2014 | 67,368 | $ 25.01 | 85 | 1.57 | $ 12.34 | $ 11.51 | $ 0.54 | $ - | $ 0.04 | $ 0.58 | 0.7% | 1.7 | - | 1.09 |
| | | 1 | | | Event 9 | 2/1/2016 | 84,168 | $ 28.23 | 85 | 1.40 | $ 13.42 | $ 13.50 | $ 0.59 | $ - | $ 0.04 | $ 0.68 | 0.7% | 1.7 | 0.64 | 0.80 |
| | | | 1 | | Event 10 | 2/1/2016 | 84,168 | $ 29.36 | 85 | 1.40 | $ 14.50 | $ 13.50 | $ 0.64 | $ - | $ 0.04 | $ 0.68 | 0.7% | 1.7 | - | 0.96 |
| 3 | | | | | Event 11 | 2/1/2018 | 100,992 | $ 32.49 | 85 | 1.57 | $ 15.68 | $ 15.31 | $ 0.69 | $ - | $ 0.04 | $ 0.77 | 0.7% | 1.7 | 0.63 | 0.85 |
| | 1 | | | | Event 12 | 2/1/2018 | 100,992 | $ 33.52 | 85 | 1.57 | $ 16.66 | $ 15.31 | $ 0.74 | $ - | $ 0.04 | $ 0.77 | 0.7% | 1.7 | - | 1.09 |
| | | 1 | | | Event 13 | 2/1/2020 | 117,792 | $ 36.17 | 85 | 1.40 | $ 17.55 | $ 16.95 | $ 0.78 | $ - | $ 0.04 | $ 0.85 | 0.7% | 1.7 | 0.64 | 0.80 |
| | | | 1 | | Event 14 | 2/1/2020 | 117,792 | $ 37.10 | 85 | 1.40 | $ 18.44 | $ 16.95 | $ 0.82 | $ - | $ 0.04 | $ 0.85 | 0.7% | 1.7 | - | 0.96 |
| 3 | | | | | Event 15 | 2/1/2022 | 134,616 | $ 39.67 | 85 | 1.57 | $ 19.41 | $ 18.44 | $ 0.86 | $ - | $ 0.04 | $ 0.93 | 0.7% | 1.7 | 0.63 | 0.85 |
| | 1 | | | | Event 16 | 2/1/2022 | 134,616 | $ 40.52 | 85 | 1.57 | $ 20.22 | $ 18.44 | $ 0.90 | $ - | $ 0.04 | $ 0.93 | 0.7% | 1.7 | - | 1.09 |
| | | 1 | | | Event 17 | 2/1/2024 | 151,416 | $ 42.70 | 85 | 1.40 | $ 20.95 | $ 19.79 | $ 0.93 | $ - | $ 0.04 | $ 0.99 | 0.7% | 1.7 | 0.64 | 0.80 |
| | | | 1 | | Event 18 | 2/1/2024 | 151,416 | $ 43.46 | 85 | 1.40 | $ 21.68 | $ 19.79 | $ 0.96 | $ - | $ 0.04 | $ 0.99 | 0.7% | 1.7 | - | 0.96 |
| 3 | | | | | Event 19 | 2/1/2026 | 168,240 | $ 45.58 | 85 | 1.57 | $ 22.48 | $ 21.01 | $ 1.00 | $ - | $ 0.04 | $ 1.06 | 0.7% | 1.7 | 0.63 | 0.85 |
| | 1 | | | | Event 20 | 2/1/2026 | 168,240 | $ 46.27 | 85 | 1.57 | $ 23.14 | $ 21.01 | $ 1.03 | $ - | $ 0.04 | $ 1.06 | 0.7% | 1.7 | - | 1.09 |

Note: In the above output tables "black" entry dates correspond to planned outages
"red" entry dates correspond to special outages just to add or replace catalyst

## Table 6-9. Case Study 2 (2b): 3+1 Configuration, Plate Catalyst in Layer 1, Change up to 550 Days Late

| Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | | Nearest Outage Analysis | | | | | Cost Components | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Date | Operating Hours | Total Cost | dNOx | NH3slip | Catalyst | Reagent | Labor | Electricity | IOx Credit | dP | SO2 Conv | dP | RP/RPo ( used) | RP/RPo (new) |
| | | | | | | | hrs | $ 10^6 | % | ppm | $ 10^6 | $ 10^6 | $ 10^6 | $ 10^6 | $ 10^6 | $ 10^6 | % | in H2O | | |
| 1 | 1 | 1 | | | Start | 5/1/2002 | 0 | $ - | 85 | 0.1 | $ - | $ - | $ - | $ - | $ - | $ - | 0.5% | 1.3 | | 1.00 |
| 3 | | | | | Event 1 | 2/1/2008 | 22,032 | $ 10.87 | 32 | 2.00 | $ 1.93 | $ 4.80 | $ 0.08 | $ - | $ 3.88 | $ 0.19 | 0.5% | 1.2 | 0.47 | 0.64 |
| | | | 1 | | Event 2 | 2/1/2010 | 34,488 | $ 20.13 | 19 | 2.00 | $ 3.38 | $ 6.92 | $ 0.14 | $ - | $ 9.40 | $ 0.28 | 0.7% | 1.7 | 0.41 | 0.74 |
| 3 | | | | | Event 3 | 2/1/2012 | 51,288 | $ 27.49 | 32 | 2.00 | $ 4.96 | $ 9.34 | $ 0.21 | $ - | $ 12.57 | $ 0.41 | 0.7% | 1.7 | 0.47 | 0.69 |
| | 1 | | | | Event 4 | 2/1/2014 | 68,112 | $ 36.20 | 18 | 2.00 | $ 6.15 | $ 11.54 | $ 0.26 | $ - | $ 17.72 | $ 0.53 | 0.7% | 1.7 | 0.40 | 0.71 |
| | | 1 | | | Event 5 | 2/1/2016 | 84,912 | $ 43.59 | 20 | 2.00 | $ 7.23 | $ 13.53 | $ 0.31 | $ - | $ 21.89 | $ 0.63 | 0.7% | 1.7 | 0.42 | 0.69 |
| | | | 1 | | Event 6 | 2/1/2018 | 101,736 | $ 49.88 | 26 | 2.00 | $ 8.21 | $ 15.34 | $ 0.36 | $ - | $ 25.25 | $ 0.72 | 0.7% | 1.7 | 0.45 | 0.69 |
| 3 | | | | | Event 7 | 2/1/2020 | 118,536 | $ 55.16 | 33 | 2.00 | $ 9.29 | $ 16.98 | $ 0.40 | $ - | $ 27.70 | $ 0.80 | 0.7% | 1.7 | 0.48 | 0.74 |
| | 1 | | | | Event 8 | 2/1/2022 | 135,360 | $ 60.12 | 24 | 2.00 | $ 10.09 | $ 18.46 | $ 0.44 | $ - | $ 30.25 | $ 0.87 | 0.7% | 1.7 | 0.44 | 0.74 |
| | | 1 | | | Event 9 | 2/1/2024 | 152,160 | $ 64.52 | 25 | 2.00 | $ 10.82 | $ 19.81 | $ 0.47 | $ - | $ 32.47 | $ 0.94 | 0.7% | 1.7 | 0.44 | 0.69 |
| | | | 1 | | Event 10 | 2/1/2026 | 168,984 | $ 68.78 | 26 | 2.00 | $ 11.49 | $ 21.04 | $ 0.51 | $ - | $ 34.75 | $ 1.00 | 0.7% | 1.7 | 0.45 | 0.69 |
| 3 | | | | | Event 11 | 2/1/2028 | 185,784 | $ 72.36 | 33 | 2.00 | $ 12.21 | $ 22.14 | $ 0.53 | $ - | $ 36.41 | $ 1.06 | 0.7% | 1.7 | 0.48 | 0.74 |
| | 1 | | | | Event 12 | 2/1/2030 | 202,608 | $ 75.71 | 24 | 2.00 | $ 12.76 | $ 23.15 | $ 0.56 | $ - | $ 38.13 | $ 1.11 | 0.7% | 1.7 | 0.44 | 0.74 |
| | | 1 | | | Event 13 | 2/1/2032 | 219,408 | $ 78.69 | 25 | 2.00 | $ 13.25 | $ 24.06 | $ 0.58 | $ - | $ 39.64 | $ 1.15 | 0.7% | 1.7 | 0.44 | 0.69 |
| | | | 1 | | Event 14 | 2/1/2034 | 236,232 | $ 81.57 | 26 | 2.00 | $ 13.70 | $ 24.89 | $ 0.60 | $ - | $ 41.18 | $ 1.20 | 0.7% | 1.7 | 0.45 | 0.69 |
| 3 | | | | | Event 15 | 2/1/2036 | 253,032 | $ 83.99 | 33 | 2.00 | $ 14.19 | $ 25.64 | $ 0.62 | $ - | $ 42.30 | $ 1.23 | 0.7% | 1.7 | 0.48 | 0.74 |
| | 1 | | | | Event 16 | 2/1/2038 | 269,856 | $ 86.26 | 24 | 2.00 | $ 14.56 | $ 26.32 | $ 0.64 | $ - | $ 43.47 | $ 1.27 | 0.7% | 1.7 | 0.44 | 0.74 |
| | | 1 | | | Event 17 | 2/1/2040 | 286,656 | $ 88.28 | 25 | 2.00 | $ 14.90 | $ 26.94 | $ 0.66 | $ - | $ 44.48 | $ 1.30 | 0.7% | 1.7 | 0.44 | 0.69 |
| | | | 1 | | Event 18 | 2/1/2042 | 303,480 | $ 90.22 | 26 | 2.00 | $ 15.20 | $ 27.50 | $ 0.67 | $ - | $ 45.53 | $ 1.33 | 0.7% | 1.7 | 0.45 | 0.69 |
| 3 | | | | | Event 19 | 2/1/2044 | 320,280 | $ 91.86 | 33 | 2.00 | $ 15.53 | $ 28.01 | $ 0.68 | $ - | $ 46.28 | $ 1.35 | 0.7% | 1.7 | 0.48 | 0.74 |
| | 1 | | | | Event 20 | 2/1/2046 | 337,104 | $ 93.40 | 24 | 2.00 | $ 15.78 | $ 28.47 | $ 0.70 | $ - | $ 47.07 | $ 1.38 | 0.7% | 1.7 | 0.44 | 0.74 |

Note: In the above output tables "black" entry dates correspond to planned outages
"red" entry dates correspond to special outages just to add or replace catalyst

## Table 6-10. Case Study 2 (2c): 3+1 Configuration, Plate Catalyst in Layer 1, Change up to 365 Days Early or Late

| Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | | Date | Operating Hours | Total Cost | dNOx | NH3slip | Cost Components | | | | | | SO2 Conv | dP | RP/RPo ( used) | RP/RPo (new) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | hrs | $ 10^6 | % | ppm | Catalyst $ 10^6 | Reagent $ 10^6 | Labor $ 10^6 | Electricity $ 10^6 | lOx Credit $ 10^6 | dP $ 10^6 | % | in H2O | | |
| 1 | 1 | 1 | | | Start | 5/1/2002 | 0 | $ - | 85 | 0.1 | $ - | $ - | $ - | $ - | $ - | $ - | 0.5% | 1.3 | | 1.00 |
| 3 | | | | | Event 1 | 2/1/2006 | 14,688 | $ 6.01 | 82 | 2.00 | $ 2.13 | $ 3.65 | $ 0.08 | $ - | $ 0.02 | $ 0.14 | 0.5% | 1.2 | 0.59 | 0.71 |
| | | | 1 | | Event 2 | 6/7/2007 | 21,384 | $ 12.16 | 61 | 2.00 | $ 3.77 | $ 5.17 | $ 0.16 | $ 2.30 | $ 0.55 | $ 0.20 | 0.7% | 1.7 | 0.55 | 0.89 |
| 3 | | | | | Event 3 | 6/20/2010 | 36,849 | $ 18.68 | 66 | 2.00 | $ 5.49 | $ 7.75 | $ 0.23 | $ 4.00 | $ 0.86 | $ 0.35 | 0.7% | 1.7 | 0.56 | 0.75 |
| | 1 | | | | Event 4 | 7/6/2011 | 45,764 | $ 23.30 | 64 | 2.00 | $ 6.84 | $ 9.08 | $ 0.29 | $ 5.50 | $ 1.17 | $ 0.42 | 0.7% | 1.7 | 0.56 | 0.83 |
| | | 1 | | | Event 5 | 12/26/2012 | 57,743 | $ 28.04 | 64 | 2.00 | $ 8.10 | $ 10.73 | $ 0.35 | $ 6.90 | $ 1.46 | $ 0.51 | 0.7% | 1.7 | 0.56 | 0.79 |
| | | | 1 | | Event 6 | 6/19/2014 | 69,724 | $ 32.41 | 67 | 2.00 | $ 9.27 | $ 12.27 | $ 0.41 | $ 8.20 | $ 1.69 | $ 0.58 | 0.7% | 1.7 | 0.57 | 0.78 |
| 3 | | | | | Event 7 | 2/1/2016 | 83,688 | $ 36.07 | 58 | 2.00 | $ 10.57 | $ 13.92 | $ 0.46 | $ 8.20 | $ 2.25 | $ 0.67 | 0.7% | 1.7 | 0.55 | 0.80 |
| | 1 | | | | Event 8 | 5/28/2017 | 94,549 | $ 39.75 | 64 | 2.00 | $ 11.59 | $ 15.13 | $ 0.51 | $ 9.33 | $ 2.48 | $ 0.73 | 0.7% | 1.7 | 0.56 | 0.84 |
| | | 1 | | | Event 9 | 12/10/2018 | 107,051 | $ 43.35 | 64 | 2.00 | $ 12.53 | $ 16.42 | $ 0.55 | $ 10.37 | $ 2.69 | $ 0.79 | 0.7% | 1.7 | 0.56 | 0.77 |
| | | | 1 | | Event 10 | 2/1/2020 | 116,112 | $ 45.21 | 85 | 1.93 | $ 13.41 | $ 17.30 | $ 0.59 | $ 10.37 | $ 2.69 | $ 0.84 | 0.7% | 1.7 | 0.60 | 0.81 |
| 3 | | | | | Event 11 | 8/30/2021 | 129,959 | $ 48.61 | 69 | 2.00 | $ 14.41 | $ 18.55 | $ 0.63 | $ 11.29 | $ 2.84 | $ 0.90 | 0.7% | 1.7 | 0.57 | 0.82 |
| | 1 | | | | Event 12 | 2/11/2023 | 141,701 | $ 51.48 | 65 | 2.00 | $ 15.17 | $ 19.54 | $ 0.67 | $ 12.14 | $ 3.01 | $ 0.95 | 0.7% | 1.7 | 0.56 | 0.84 |
| | | 1 | | | Event 13 | 8/23/2024 | 154,159 | $ 54.19 | 64 | 2.00 | $ 15.89 | $ 20.51 | $ 0.70 | $ 12.93 | $ 3.17 | $ 1.00 | 0.7% | 1.7 | 0.56 | 0.77 |
| | | | 1 | | Event 14 | 2/1/2026 | 166,560 | $ 56.17 | 57 | 2.00 | $ 16.55 | $ 21.41 | $ 0.73 | $ 12.93 | $ 3.50 | $ 1.04 | 0.7% | 1.7 | 0.55 | 0.76 |
| 3 | | | | | Event 15 | 7/3/2027 | 178,254 | $ 58.58 | 69 | 2.00 | $ 17.30 | $ 22.21 | $ 0.76 | $ 13.62 | $ 3.61 | $ 1.08 | 0.7% | 1.7 | 0.57 | 0.82 |
| | 1 | | | | Event 16 | 12/19/2028 | 190,137 | $ 60.74 | 65 | 2.00 | $ 17.87 | $ 22.96 | $ 0.79 | $ 14.26 | $ 3.74 | $ 1.12 | 0.7% | 1.7 | 0.56 | 0.84 |
| | | 1 | | | Event 17 | 7/7/2030 | 202,729 | $ 62.79 | 64 | 2.00 | $ 18.41 | $ 23.70 | $ 0.81 | $ 14.85 | $ 3.86 | $ 1.16 | 0.7% | 1.7 | 0.56 | 0.77 |
| | | | 1 | | Event 18 | 10/28/2031 | 213,966 | $ 64.61 | 67 | 2.00 | $ 18.91 | $ 24.31 | $ 0.84 | $ 15.41 | $ 3.96 | $ 1.19 | 0.7% | 1.7 | 0.57 | 0.78 |
| 3 | | | | | Event 19 | 5/5/2033 | 226,325 | $ 66.46 | 69 | 2.00 | $ 19.47 | $ 24.94 | $ 0.86 | $ 15.93 | $ 4.04 | $ 1.22 | 0.7% | 1.7 | 0.57 | 0.82 |
| | 1 | | | | Event 20 | 10/21/2034 | 238,187 | $ 68.08 | 65 | 2.00 | $ 19.90 | $ 25.51 | $ 0.88 | $ 16.41 | $ 4.13 | $ 1.25 | 0.7% | 1.7 | 0.56 | 0.84 |

Note: In the above output tables "black" entry dates correspond to planned outages
"red" entry dates correspond to special outages just to add or replace catalyst

## Table 6-11. Twenty Year Summary Case Study No. 2

| | Base Case * | | | |
|---|---|---|---|---|
| **Summary Report** | **3+1Plate (1c)** | **650 Days Early (2a)** | **550 Days late (2b)** | **Plus/Minus 365 Days (2c)** |
| As of Date | **12/31/22** | **12/31/22** | **12/31/22** | **12/31/22** |
| Total Cost NPV | **$ 49,755,460** | **$ 48,344,474** | **$ 67,384,930** | **$ 50,143,851** |
| Catalyst NPV | $ 15,302,859 | $ 20,766,192 | $ 11,914,383 | $ 15,853,649 |
| Reagent NPV | $ 19,581,103 | $ 20,539,303 | $ 19,966,617 | $ 19,382,780 |
| Labor NPV | $ 684,325 | $ 917,961 | $ 522,463 | $ 697,797 |
| Electricity NPV | $ 9,757,481 | $ 1,338,352 | $ 1,706,319 | $ - |
| NOx Credit NPV | $ 3,476,486 | $ 3,775,303 | $ 32,310,902 | $ 13,234,281 |
| dP NPV | $ 953,206 | $ 1,007,364 | $ 964,246 | $ 975,345 |
| Catalyst Layers Installed | 12 | 16 | 9 | 12 |

* The base case for Case Study 2 is configuration 1C from Case Study 1. In this case, the catalyst event was allowed to occur 120 days early or 90 days after reaching the minimum Reactor Potential.

# 7

# COMMERCIALIZATION

## 7.1 Background

Considering the success of the *in situ* Catalyst Activity demonstration during this project, FERCo intends to commercialize the technology. At this time FERCo intends to commercialize the technology in-house as another specialized instrument to be marketed under our name.

The primary purchaser of the *In situ* Catalyst Activity device will be the coal-fired utility industry. Figure 7-1 shows the coal-fired capacity that has, or is projected to install SCR systems through 2012. By 2012 the total installed capacity of SCR units on coal-fired boilers will be on the order of 125 GW (Cichanowicz, et al., 2006). This installed capacity represents over 300 SCR reactors for which the *in situ* activity device is appropriate.

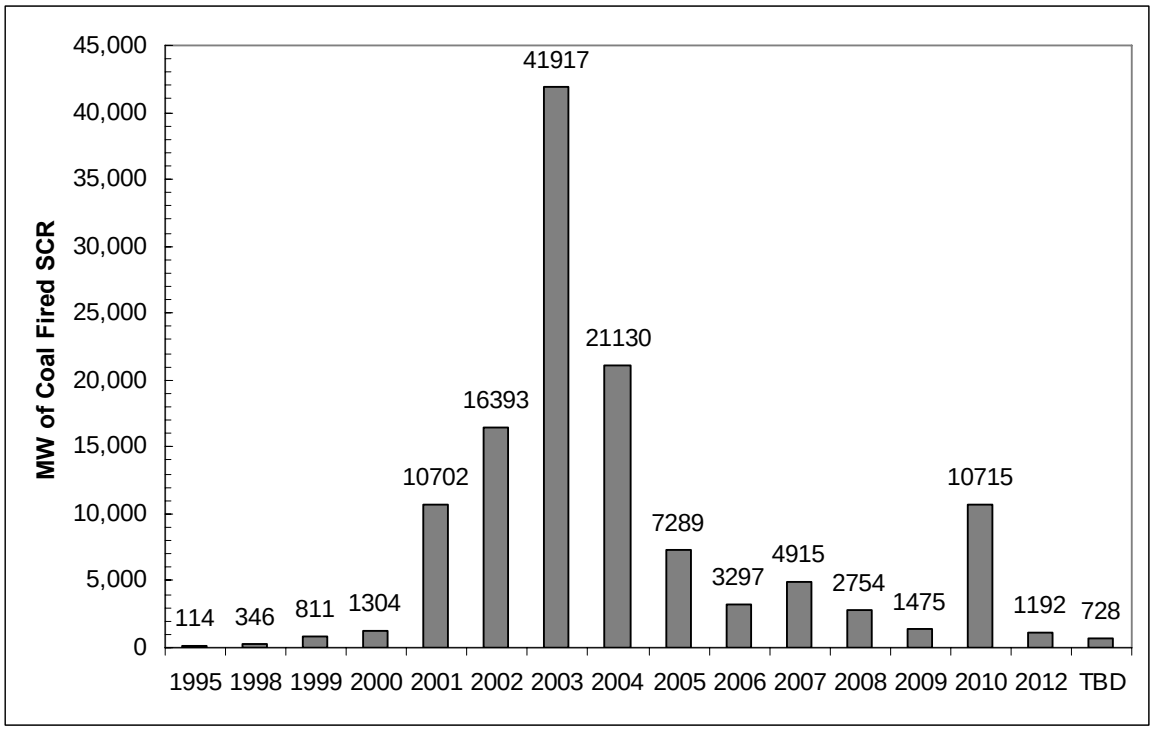



**Figure 7-1. SCR Retrofits by Startup Year (Cichanowicz, et al., 2006)**

It is anticipated that the coal-fired utility industry will use the device for two purposes. First, as it was initially intended and demonstrated, to monitor Catalyst Activity. In addition, many utilities are considering operating their SCR reactors at lower and lower loads where they will be below the catalyst vendors recommended minimum operating temperature for the catalyst. At this

temperature, ammonia can react with $SO_3$ forming ammonium bisulfate (ABS). This sequence of events is shown in Figure 7-2:

- At full-load, the Reactor Potential is above the minimum required to achieve the desired $NO_x$ reduction and minimum ammonia slip.
- As the load is decreased, the Reactor Potential increases due to the lower flue gas flow rate at low load.
- As the unit continues to operate at low load, below the minimum operating temperature, ABS forms and deposits on the catalyst. This, in turn, reduces the Reactor Potential.
- When the unit returns to full-load the Reactor Potential decreases as the flue gas flow rate increases.
- At the higher flue gas temperatures associated with full-load, the ABS sublimes and the Reactor Potential returns to its initial full-load value.

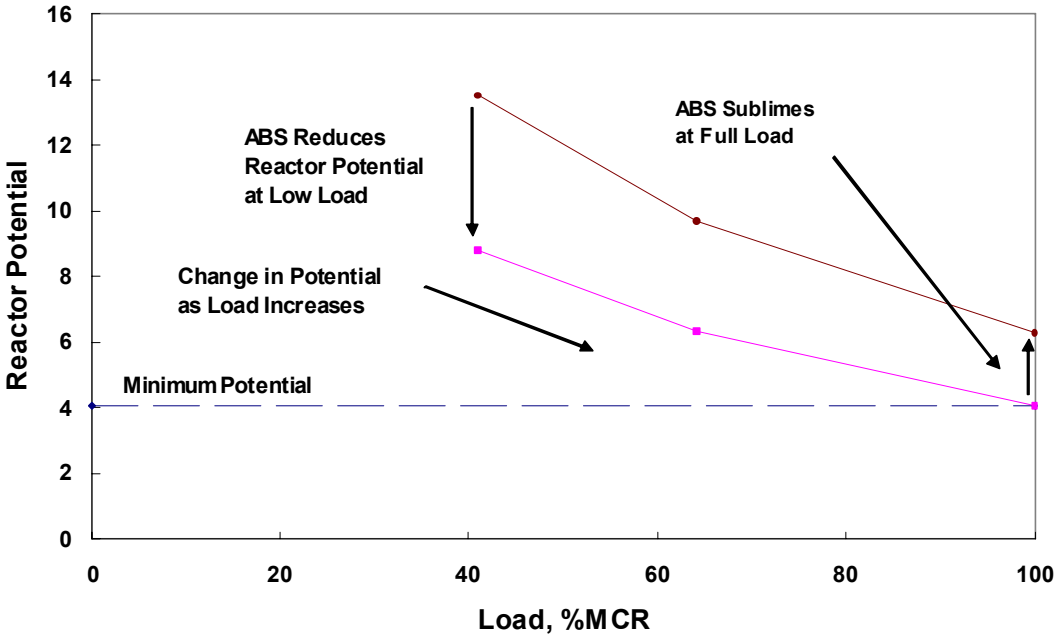



**Figure 7-2. Change in Reactor Potential with Load and ABS Deposition**

The utility needs a way to monitor Reactor Potential to determine how long they can operate at low loads and how much Reactor Potential they can afford to lose. They can only operate for a period such that when they return to full load they are above the "minimum Reactor Potential" needed to produce the desired $NO_x$ reduction with the required ammonia slip. The *in situ* device is ideally suited to provide this information in essentially real-time.

In addition to the coal-fired utility industry, it is anticipated that there is a need for a similar measurement in gas turbine SCR systems. The *in situ* measuring device for this application is anticipated to be simpler than the one for the coal-fired fleet.

## 7.2 Anticipated Hardware Configuration

For the coal-fired SCR applications, two basic configurations are anticipated. The first configuration would have all of the gas analysis, data acquisition, and valve switching subsystems in a single cabinet dedicated to one SCR system. In the second system, a cabinet containing the switching valves would be dedicated to each SCR unit. The gas analysis instrumentation and data acquisition systems (similar to that built for Gorgas, Figure 3-3) would be housed in a separate cart. For plants with multiple SCR systems at one site, a utility may opt for this second configuration. With this second configuration they would only have to purchase one set of gas analyzers as the cart could be moved from unit to unit.

For the gas turbine application a more simple, manually operated, system is anticipated. In fact, it may only involve a single set of $NO_x/O_2$ analyzers, and possibly an ammonia injection system that can be installed through a port only when an activity measurement is to be made.

FERCo has already reviewed the hardware fabricated for the 2006 ozone season demonstration at Gorgas and has made design changes to simplify the system.

## 7.3 Steps to Commercialization

FERCo has already taken steps to commercialize the technology. A U.S. Patent has been applied for (Muzio and Smith, 2005). The patent application has been published but as of yet not reviewed by the U.S. Patent Office.

FERCo has made presentations of the Gorgas results at a number of Technical Conferences.

- 2005 EPRI SCR Workshop
- 2006 DOE Environmental Controls Conference
- 2006 EPRI SCR Workshop
- 2007 Reinhold $NO_x$ Roundtable

In addition, FERCo has highlighted the *In situ* Activity device at the following venues where FERCo had an exhibit booth:

- 2006 Mega Symposium
- 2006 Reinhold $NO_x$ Roundtable
- 2007 Reinhold $NO_x$ Roundtable

The *in situ* device has recently been incorporated as a key measurement system in a TXU/EPRI pilot plant investigating SCR for Texas Lignite. FERCo is conducting *in situ* activity measurements on this pilot plant remotely from our California offices via the internet.

FERCo has begun formal commercialization of the systems. This has involved talking to selected utilities who we think might benefit from the technology. One utility has already incorporated the required ports into the reactor design of a new SCR to accommodate the *in situ* device.

In the near future about a dozen utilities will be contacted via e-mail announcing the commercial availability of the system. In this e-mail we plan to offer to supply the first three systems at essentially cost to gain some commercial experience.

Extensive marketing of the system will not take place until a few units have been installed and any “bugs” worked out.

## 7.4 Services

In addition to selling the *in situ* hardware, FERCo anticipates offering utilities services that will include both (1) field services of the hardware, and (2) testing services whereby activity tests would be conducted by FERCo at a frequency specified by the utility.

# 8

# SUMMARY AND CONCLUSIONS

The results of this study over two ozone seasons successfully demonstrated a method to determine SCR Catalyst Activity *in situ* on a layer-by-layer basis. This will become a valuable tool to utilities operating SCR rectors on coal fired units as they transition from seasonal (ozone season; May 1 to September 30) operation, to year round operation. With year round operation there will be diminished opportunity to obtain physical catalyst samples from the reactor for laboratory determination of activity.

The following conclusions can be drawn from the current study.

- The current *in situ* technique directly measures the Reactor Potential. The Reactor Potential is the parameter that determines the overall performance of the SCR reactor. With the laboratory activity measurement, an estimate of the catalyst blockage is needed to determine Reactor Potential.

- Measurements can be made on a layer-by-layer basis within the reactor. Additionally, the ability to run the *in situ* test any time the reactor is on line provides a larger data set upon which to quantify deactivation rates compared to once a year physical sampling.

- There was excellent quantitative agreement in the *in situ* and laboratory activity measurements of a new layer of plate catalyst installed at the start of the 2006 ozone season. Since the catalyst was new without any blockage a direct comparison could be made without the need to access blockage.

- In comparing the *in situ* measurements to laboratory measurements for older catalyst layers that have experienced some blockage, the accurate assessment of blockage becomes a key factor in determining Reactor Potential from the laboratory activity measurements. The *in situ* technique directly measures Reactor Potential.

- The *in situ* results can be easily integrated into catalyst management software such as EPRI's CatReact™ Program to aid in making informed catalyst management decisions.

Both the laboratory and in situ test methodologies have advantages and disadvantages as indicated in Table 8-1. Overall, an important point to note is that the *in situ* technique should not be thought of as a replacement for the laboratory analysis of catalyst samples, but rather a companion measurement.

**Table 8-1. Comparison of Measurement Techniques**

| Laboratory | *In situ* |
|---|---|
| Advantages<br>• Provides accurate K determination<br>• Sample removed may also be analyzed for physical and chemical properties (surface area, poisons, etc.) | Advantages<br>• Direct measurement of RP<br>• Larger data set (testing is not dependent on outage schedule)<br>• Can test immediately after unit upset (e.g. tube leak) to assess effect on SCR operation |
| Disadvantages<br>• Relies on an estimate of blockage to calculate RP*<br>• Limited data set (samples can only be removed during outages) | Disadvantages<br>• Relies on an estimate of blockage to calculate K*<br>• $\Delta NO_x$ increase at $NH_3/NO_x$ >1 may yield slightly higher absolute RP values |

* Visual estimate of blockage, or calculated form the pressure drop across a layer.

# 9

# REFERENCES


Cichanowicz, J.E., Muzio, L.J., Hein, M.C., "*The First 100 GW of SCR in the US – What Have We Learned?*", paper 129, 2006 Power Plant Air Pollution Control "Mega Symposium", August 2006.

Muzio, L.J., Smith, R.A., "*In Line Localized Monitoring of Catalyst Activity in Selective Catalytic $NO_x$ Reduction Systems*", U.S. Patent Application 20050255605, Filed April 21, 2005.

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